Investigation of a Linear Gravity and Magnetic Anomaly in Northwestern Ohio and East-Central Indiana

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation with distinction in Geological Sciences in the undergraduate colleges of The Ohio State University

by

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ABSTRACT

Geophysical investigations indicate that the source of a large, linear gravity and magnetic anomaly extending from east-central Indiana through northwestern Ohio may be an intrusive mafic dike or dike complex, that intruded the basement rocks of the region along preexisting fractures or faults. Geophysical modeling suggests that the source of the anomaly may be between 1000 meters and 3500 meters below the land surface and dipping to the southeast at between 35 degrees and 71 degrees. Modeling has also suggested that the density of the body is approximately 2.8g/cc and its effective magnetic susceptibility contrast is approximately 2596 x 10^6 cgs. Gravity and magnetic anomaly data indicate apparent left-lateral offset possibly due to left-lateral movement in the basement rocks prior to intrusion, or left-lateral strike-slip faulting that occurred after emplacement of the body. The dike complex also appears to be related to hydrocarbon accumulations in the overlying Trenton Limestone in Indiana, Ohio, and the Albion-Scipio oil field of Michigan.

I. INTRODUCTION

The purpose of this paper is to examine a northeasterly trending, linear, geophysical anomaly that extends approximately 260 km from Fayette County in Indiana, through Northwest Ohio, and possibly into southern Michigan (figure 1). Previously collected gravity and magnetic anomaly data from Indiana and Ohio are used to locate and model the anomaly source in two dimensions. This paper focuses on the portion of the anomaly source that exists in the Precambrian basement rock of northwestern Ohio including Mercer, Van Wert, Paulding, Defiance, and Williams counties (figure 2).

The sharp linearity of the feature and the direct correlation between positive magnetic and gravity anomaly data strongly suggest that the source is a dike-like intrusive body composed of mafic material. Henderson and Zietz (1958) used aeromagnetic data to model a portion of the anomaly located in Randolph County, Indiana and concluded that the source is, in fact, a dike. Leosewski (1985) also modeled the anomaly in east-central Indiana using both aeromagnetic and gravity data and reasoned the source to be a mafic dike complex as well. To my knowledge, no modeling of the extension of this feature into Ohio has been done; however, Jones (1988) and Lucius (1985) have described possible mafic dike-like intrusions for the source of this anomaly in northwestern Ohio.

The opinion shared by all of the aforementioned regarding the origin of the feature revolves around the idea of intrusion of mafic material through preexisting fractures or faults that are most likely associated with Keweenawan age rifting in the Precambrian basement of the region. Rifting of this type has been described in both Indiana (Henderson and Zietz , 1958) and Ohio (Shrake et al., 1991; Wickstrom et al., 1992) as well as in the Michigan Basin, where it is thought to be related to the development of the very productive Albion-Scipio oil fields (Hurley & Budros, 1990) of

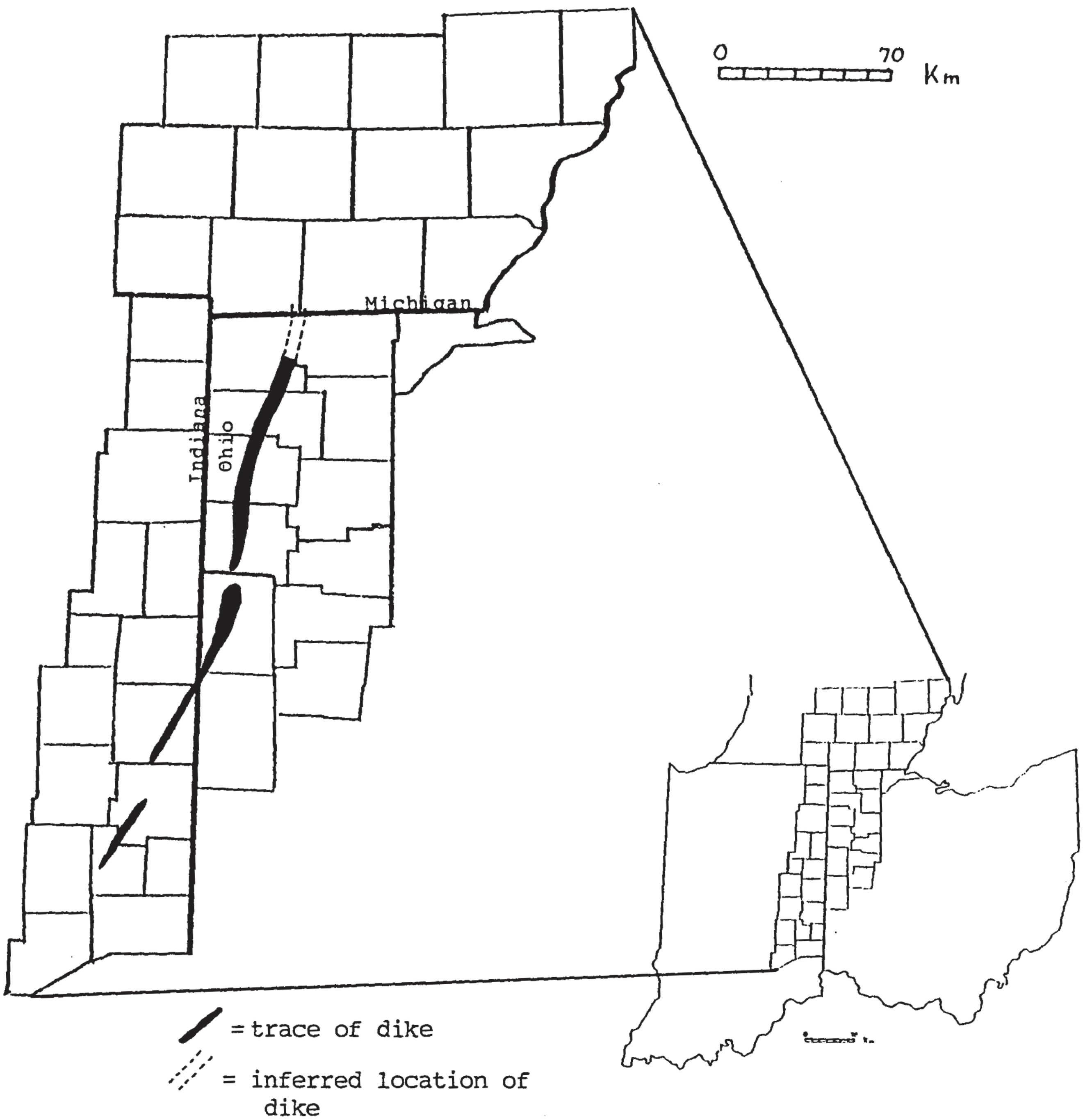

Figure 1. Spatial location of the dike in Indiana and Ohio.

= counties containing anomaly in Ohio

Figure 2. County location map of Indiana and Ohio.

southern Michigan.

Possible post-emplacement deformation is also considered here as components of this feature appear to have been left- laterally offset. A possible explanation may involve left-lateral strike-slip fault movement in areas across the dike. Such left-lateral type movement has previously been described in the subsurface of northwestern Ohio (Jones, 1988) and southern Michigan (Ells, 1962).

Finally, the potential for possible hydrocarbon accumulation related to this feature is discussed. Leosewski (1988) mentions accumulations in Indiana resulting from dolomitization of the Trenton Limestone overlying the dike intrusion. Similar hydrocarbon deposits have been found in the Trenton Limestone of Michigan (Hurley & Budros, 1990), as well as in Ohio (Leosewski, 1985).

II. GEOLOGIC SETTING OF THE REGION

Lithology

The study area lies on the stable craton of North America. The basement rocks of the region are composed mostly of Precambrian igneous rocks (figure 3) that are thought to have an anorogenic origin and a granitic/rhyolitic composition (Lucius, 1985). A recently completed drill hole in Warren county has penetrated approximately 650 m of a Precambrian lithic arenite named the Middle Run Formation, which is the only known Precambrian sedimentary unit of the state (Shrake et al., 1991; Wickstrom et al., 1992). The Precambrian rocks in the region have not been extensively studied due to the relatively small number of wells (less than 150) that have penetrated them and the fact that no Precambrian rocks are exposed at the surface in Ohio. However, the data that have been collected places the age of the rocks between 1.2 Ga and 1.5 Ga (Denison et al, 1984). It is also thought that a number of mafic intrusive bodies have invaded the Precambrian basement. Although these bodies have been interpreted as being associated with Keweenawan (Precambrian) rifting, no wells have penetrated these structures and therefore an exact age for the intrusives has not been determined (Jones, 1988).

The Precambrian basement is overlain by approximately 1-4 km of mildly deformed Phanerozoic sedimentary rocks (Lucius & von Frese, 1988). This sequence consists mainly of carbonates and shales that formed as the result of shallow seas that covered the region following the Grenville Orogeny of the Late Precambrian (Lucius, 1985), which involved the collision of Gondwana and Laurentia. The Phanerozoic deposits are laterally homogeneous and flat lying, which suggests a history of relatively limited tectonic activity; although it is thought that at least one major period of uplift and erosion followed by continued deposition has occurred since the Silurian. The carbonates and shales are blanketed by a layer of glacial tills

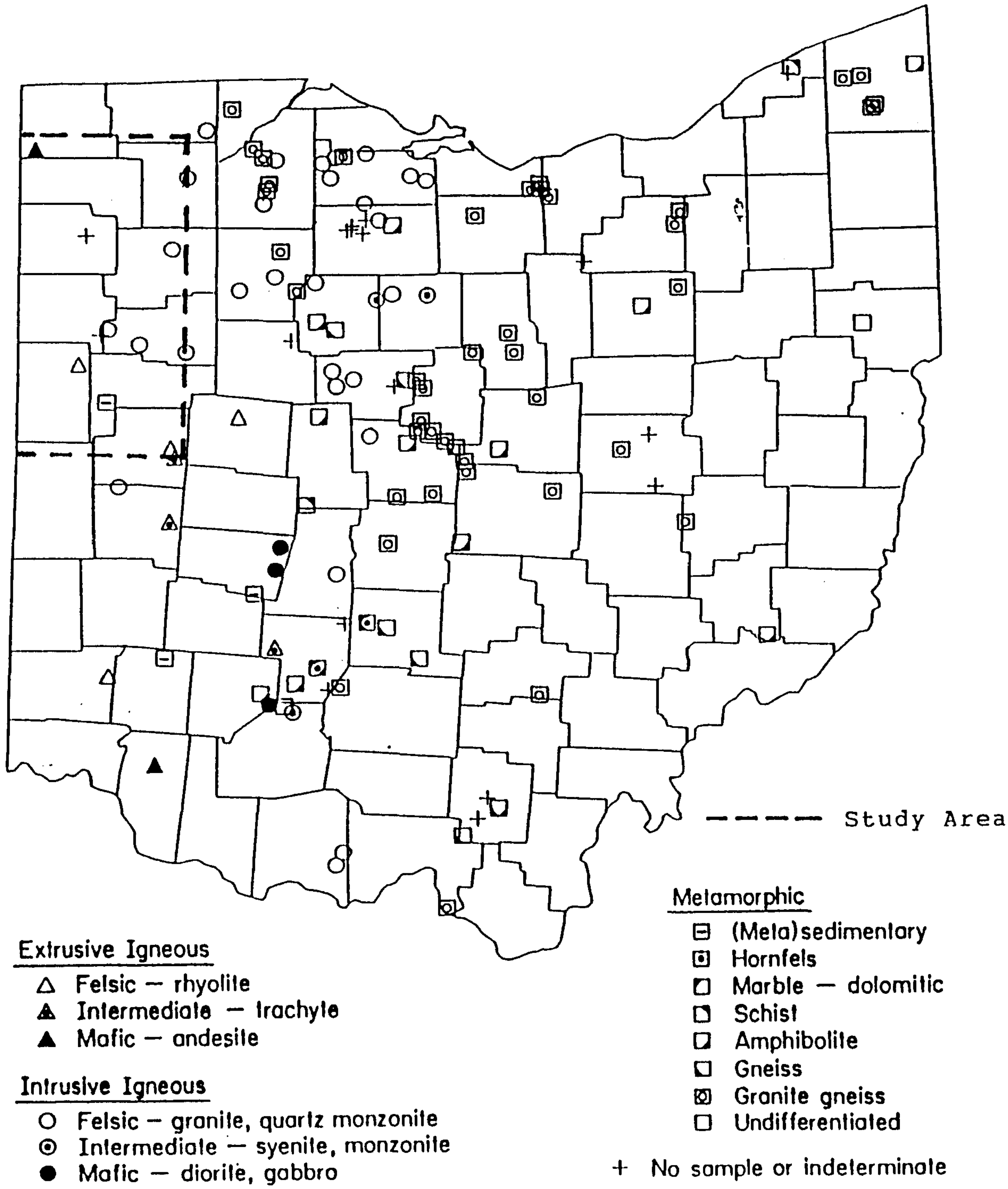

Figure 3. Ohio deep well location and associated lithologies (modified from Lucius, 1985).

and outwash that were deposited during the Pleistocene and are greater than 50 meters in thickness (Leosewski, 1985).

Tectonics

The study area is located within the Eastern Granite-Rhyolite Province of North America (figure 4). This tectonic province is characterized by unmetamorphosed felsic and intermediate intrusives and extrusives. The basement configuration of the province is characterized by broad basins and arches formed due to warping and faulting that occurred during the Paleozoic (Jones, 1988). It should be noted that these structures are the result of the basins being dropped and not of the arches being uplifted (Henderson and Zietz, 1958). The apparent dike complex under study is located within the Ohio-Indiana Platform (figure 5) and may extend into Michigan, in which case it would rest within the Michigan basin.

Rifting is also evident within the Granite-Rhyolite Province and is thought to be mainly Keweenawan (late Precambrian) in age (Leosewski, 1985) and predates the Grenville Orogeny (Shrake et al., 1991). The zones of rifting in the province are contained within the East Continent Rift Basin (Shrake et al., 1991; Wickstrom et al., 1992), which is divided into two zones: the Fort Wayne Rift Zone (FWRZ), and the Mid-Ohio Rift Zone (MORZ) (figure 6). Both zones show evidence of crustal thinning and intrusion of mafic material into the crust that are characterized by gravity and magnetic anomaly maxima (Jones, 1988; Lucius & von Frese, 1988). These zones of rifting are thought to extend north to the western edge of Lake Erie and possibly as far south as northern Alabama (Shrake et al., 1991).

The Eastern Granite-Rhyolite Province terminates to the east against the younger rocks of the Grenville Front (figure 7), which marks the western most extent of Grenville deformation and isotopic age resetting (Easton, 1986). The Grenville Province is characterized by rocks that have endured much deformation and

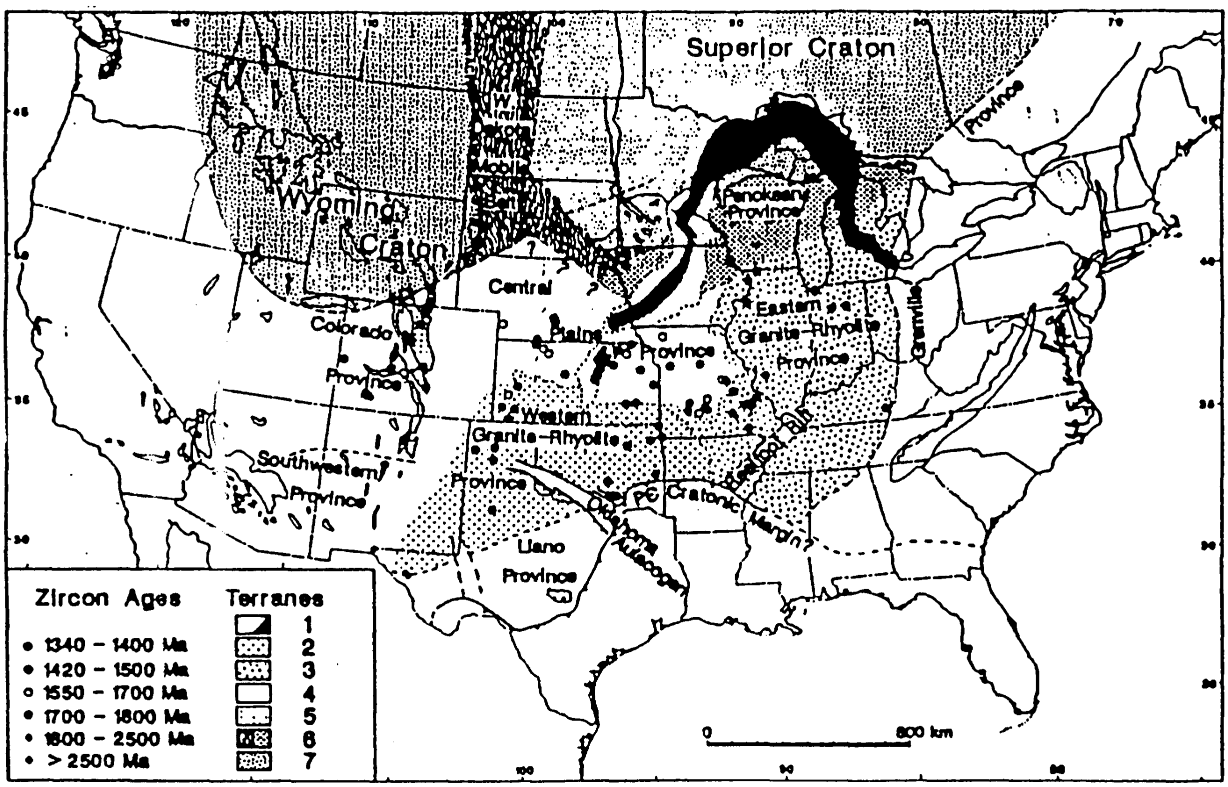

Figure 4. Tectonic provinces of the United States (Bickford, 1986).

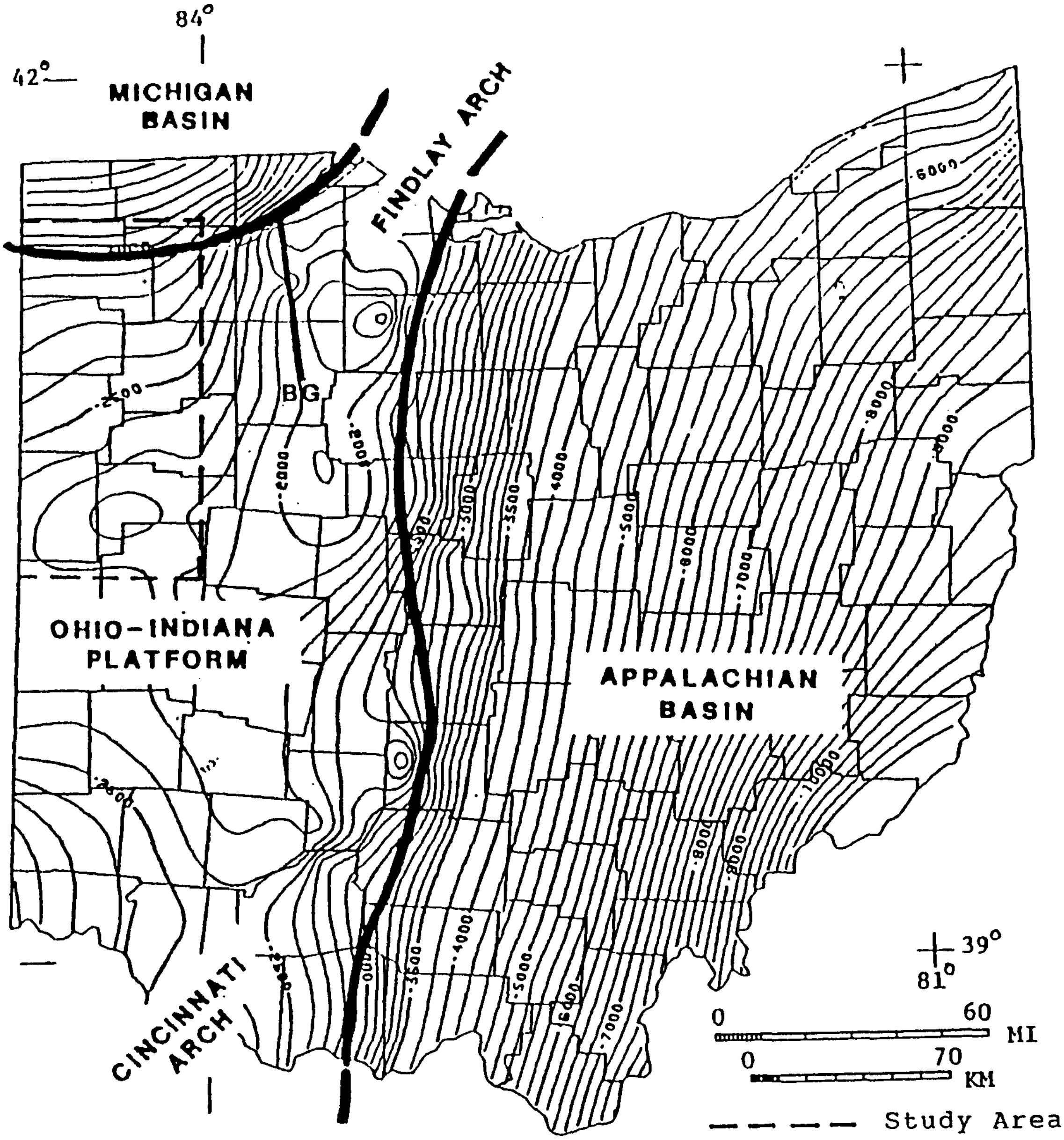

Figure 5. Basement configuration map of Ohio (modified from Lucius, 1985).

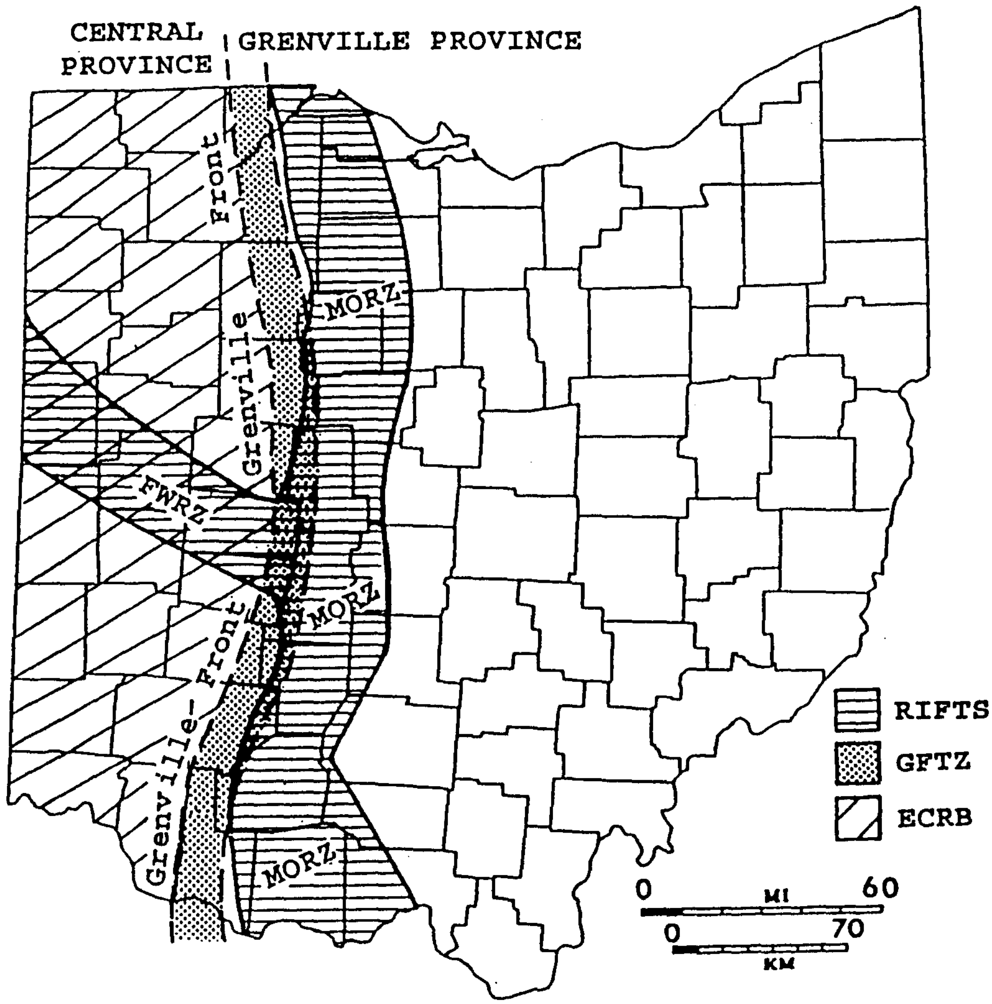

Figure 6. Tectonic features of Ohio (von Frese et al., 1994).

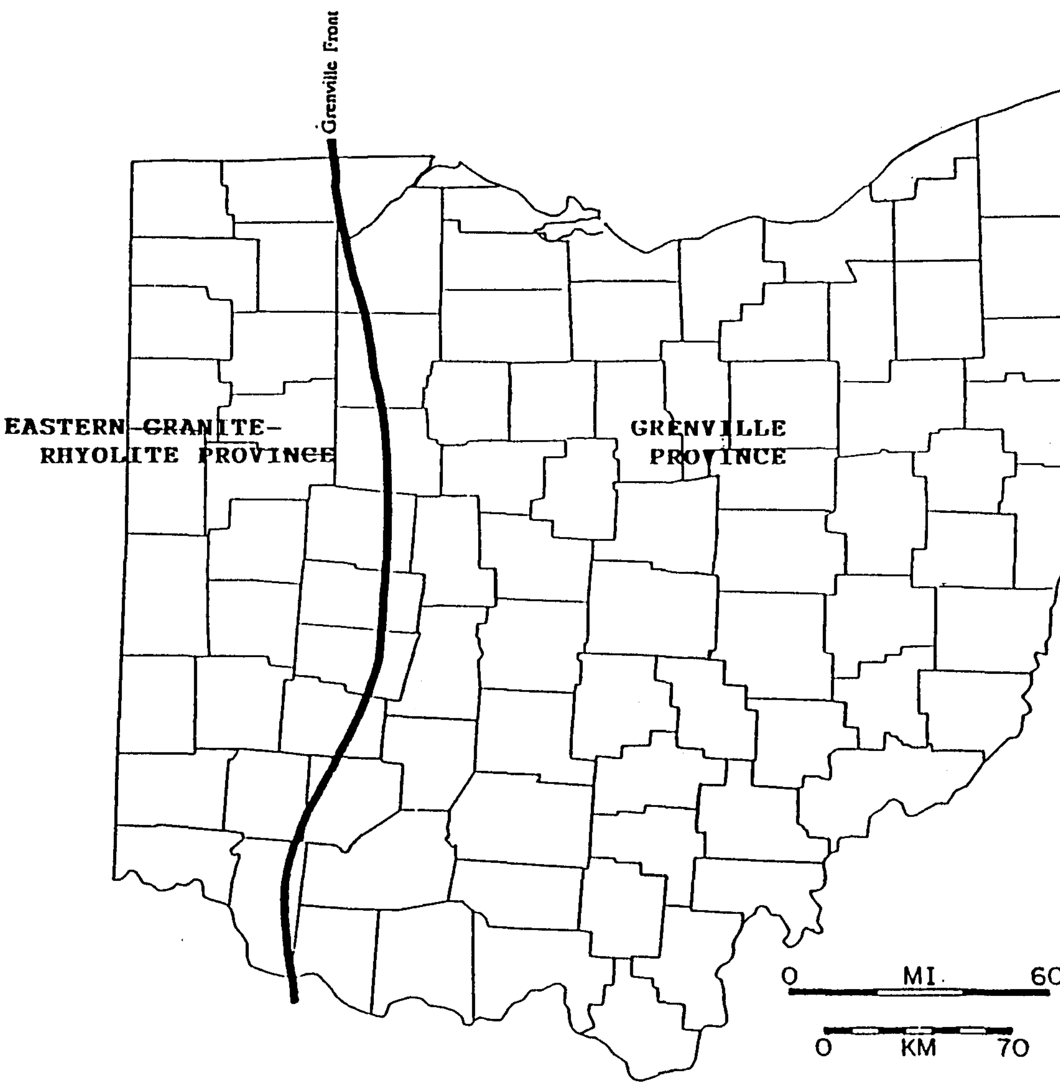

Figure 7. Major tectonic provinces of Ohio and the location of the Grenville Front (modified from Jones, 1988).

metamorphism brought on by the continent-continent collision of the Grenville Orogeny. This orogenic event began approximately 1.3 Ga (Jones, 1985) and was followed by the Keweenawan age rifting (Van Schmus et al, 1982). The Grenville Front Tectonic Zone (GFTZ) marks the limit of the suture zone in the upper crust and is characterized by a series of imbricated, eastward dipping thrust sheets (Wynne & Edwards, 1972; Davidson, 1985). Shrake et al (1991) and Wickstrom et al. (1992) propose that the Grenville Front is an exhumed structural contact and that Grenville rocks were thrust westward over the Keweenawan rift complexes after which deep erosion planed down the uplifted rocks before the initial transgression deposited the sedimentary cover.

III. GEOPHYSICAL METHODS

Gravity Method

Gravitational methods for studying features of the subsurface are based on the measurement of variations in the earth's gravitational field (Nettleton, 1940). These gravitational field variations are caused by lateral density fluctuations within the earth's crust. Differences in density are related to the rock types and structures found in the crust of a particular area. Rock density is affected by the porosity, which is most important in low density rocks, and bulk mineralogy, which is an especially important factor in higher density rocks (Judd and Shakoor, 1981). For example, extrusive igneous rocks are generally less dense than intrusives of equivalent chemistry due to the greater porosity of the extrusives, which is the result of volatiles contained within the material prior to cooling. Since intrusive rocks have very little pore space, differences in density between intrusives are produced mainly by the bulk mineralogy of the rock (Jones, 1988). The density of felsic intrusives may be controlled by the amount of monazite, zircon, and/or (Fe, Mg) silicates; whereas the density of mafic intrusives is mainly affected by the amounts of light minerals (e.g. feldspar) that they contain (Henkel, 1976).

The density of sedimentary rocks is controlled mainly by porosity, which may be also affected by the age of the rock and depth of burial (Jones, 1988). Of the three rock groups, sedimentary rocks generally have the lowest density values.

Gravity Measurements

Gravity data are collected using a device known as a gravimeter, which in principle is just an extremely sensitive weighing device consisting of a mass supported by a spring (Nettleton, 1940). Gravity data for an area can be collected by measuring minute changes in the length of the spring as the mass responds to the gravitational field. Readings are taken at various locations over a determined area and differences in gravitational intensity are recorded. The data can then be reduced and contoured to give a visual representation of the gravity signal for that area revealing various trends and anomalies.

Data collected in this manner, however, need to be corrected for various physical effects including gravitational variations associated with latitude, elevation, and the gravitational attraction of surface material (Bouguer Effect) (Nettleton, 1940). Correcting for the Bouguer Effect involves taking into account the gravitational attraction of the mass of material that exists between points of differing elevation (Nettleton, 1940). The gravity anomaly is defined as the difference between the gravity observation and the gravity effects of the various reductions (Nettleton, 1940). Data corrected in this manner can then be used to make anomaly maps for interpretation and anomaly modeling.

Gravity data can also be manipulated in various ways by filtering to enhance signal features. One useful approach is to take the vertical derivative (dG/dZ) of the Bouguer anomaly data. Taking the vertical derivative enhances the shorter wavelength components of the Bouguer anomalies that are associated with the signals of smaller, near-surface sources, and clarifies the lateral boundaries of anomalies (Xinzhu and Hinze, 1983). This facilitates the determination of the location of anomaly sources. Taking the second vertical derivative of Bouguer gravity anomalies tends to increase the resolution of anomaly details further, but higher order derivatives become increasingly problematic because they tend to enhance the effects of measurement errors and other noise.

Magnetic Method

Magnetic methods for studying features of the subsurface are based on measuring variations in the magnetic field, which are produced by the distribution of magnetized rocks (Nettleton, 1940). Magnetic anomalies are produced by sources that vary laterally in magnetization with respect to the country rock (Lucius, 1985). The magnetic intensity associated with a rock is commonly related to its effective magnetic susceptibility, which in turn reflects the concentration of magnetic minerals, mainly magnetite, that is present in the rock (Jones, 1988). Like density, magnetic susceptibility cannot necessarily be predicted by lithology (Carmichael, 1982). However, in general, sedimentary rocks have the lowest effective magnetic susceptibility, whereas mafic igneous rocks have the highest (Jones, 1988). Because of this fact, magnetic variations within the earth's crust are typically associated with the underlying, igneous and metamorphic basement rocks (Nettleton, 1940).

In the mid-continental United States, most basement rocks have lost their original, remnant magnetization through chemical and/or thermal processes; therefore, most anomalies are probably produced by magnetization resulting from the induction of magnetite (Hinze and Zietz, 1985). Magnetization in a rock can be affected by temperature, the availability of free oxygen, and other factors. In mafic intrusive rocks, for example, magnetite is produced by a process known as serpentinization that occurs after the rock is emplaced. This process involves the alteration of olivine and orthopyroxene to hydrous (Fe, Mg) silicates and magnetite (Jones, 1988). Magnetite also tends to accumulate along the margins of intrusive bodies that have invaded carbonate country rocks (Jones, 1988).

Magnetic Measurements

Magnetic data are collected using a device known as a magnetometer, which consists of a moving system containing a magnet that responds to changes in the magnetic field. The most common method of obtaining data is to place a magnetometer in an airplane and fly over the study area at a constant elevation. Readings are then made at regular intervals and the differences in magnetic intensity are recorded.

As with gravity data, corrections for certain physical phenomena must be made to the raw magnetic data in order to remove unwanted contributions to the magnetic signal that are not related to features of the subsurface. Corrections must be made for diurnal variations in the earth's magnetic field and normal variations in magnetic intensity over the earth's surface. The latter of these corresponds in a general way to latitude corrections made on gravity data (Nettleton, 1940). The magnetic anomaly is defined as the difference between the magnetic observation and the earth's normal magnetic field and external field variations (Nettleton, 1940).

Magnetic data may also be manipulated in order to filter and enhance specific parts of the signal. One common practice is to reduce the original data "to-the-pole", which has the effect of removing the horizontal magnetic signal and leaving only the vertical signal (Lucius, 1985). When this has been done, vertical derivatives can be taken to increase the resolution of the lateral boundaries of anomalies and their sources, and to compare with gravity anomalies.

IV. ANALYSIS OF GRAVITY AND MAGNETIC ANOMALIES

Gravity

The gravity data used in this study were taken from the work done by Lucius (1985) (figure 8). The data are terrain corrected Bouguer anomalies reduced for a density of 2.67 gm/cc. The first vertical derivative of the Bouguer gravity is also shown in figure 9. The gravity values include data collected by Heiskanen and Uotila (1956), G. R. Keller (Univ. of Texas, El Paso), W. J. Hinze (Purdue Univ.), and were also obtained from the USGS on an open-file computer tape. The data have been registered to a 2-km Cartesian coordinate grid using a minimum curvature computer program and include all of Ohio plus a minimum rind of 40 kilometers (Lucius, 1985). For this study, the original data file of 256 columns and 256 rows has been reduced to 32 columns and 64 rows to examine only the area surrounding the proposed dike in northwestern Ohio.

Figure 10 shows the complete Bouguer gravity of the study area. This plot reveals an elongated gravity high in the southwest corner of the study area that extends from Mercer county into Van Wert county, striking northeast. This represents the dike feature under study. From this figure, it is difficult to determine the location of, and extent to which the anomaly continues to the north. It appears that the large gravity low in the center of the figure has terminated or interrupted the anomaly signal.

The first vertical derivative of gravity was computed using the Fourier 2-D computer program and gives a much improved picture with regard to the spatial location and extent of the dike (figure 11). The major feature revealed by taking the first vertical derivative is the elongated gravity high in the upper-center of the figure that extends through Defiance County and has a northeast strike identical to that of the body to the south. Due to the fact that this feature has the same geometry and orientation, it is reasonable to interpret it as the northern extension of the dike. The

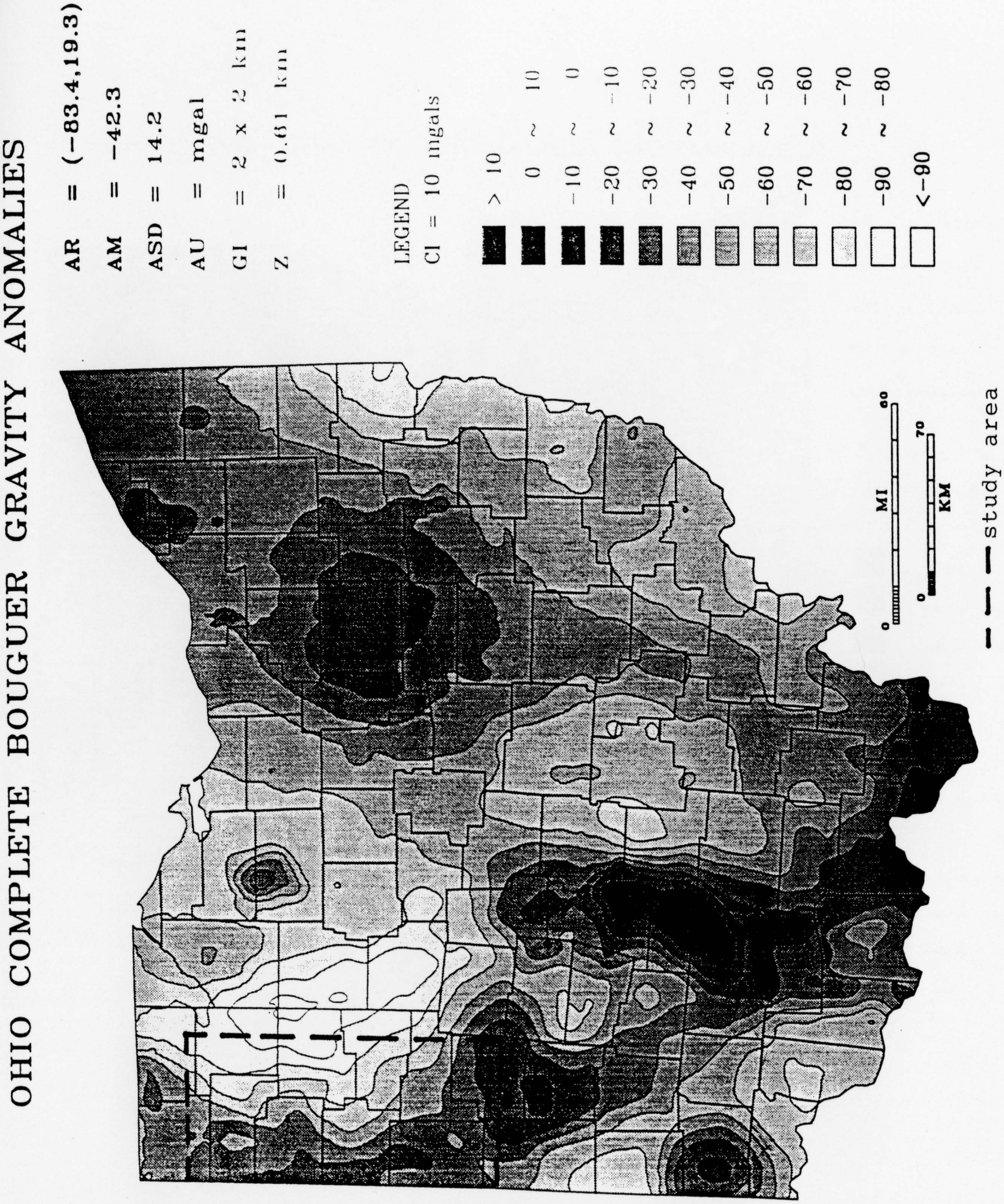

Figure 8. Complete Bouguer gravity anomalies of Ohio (von Frese et al., 1995).

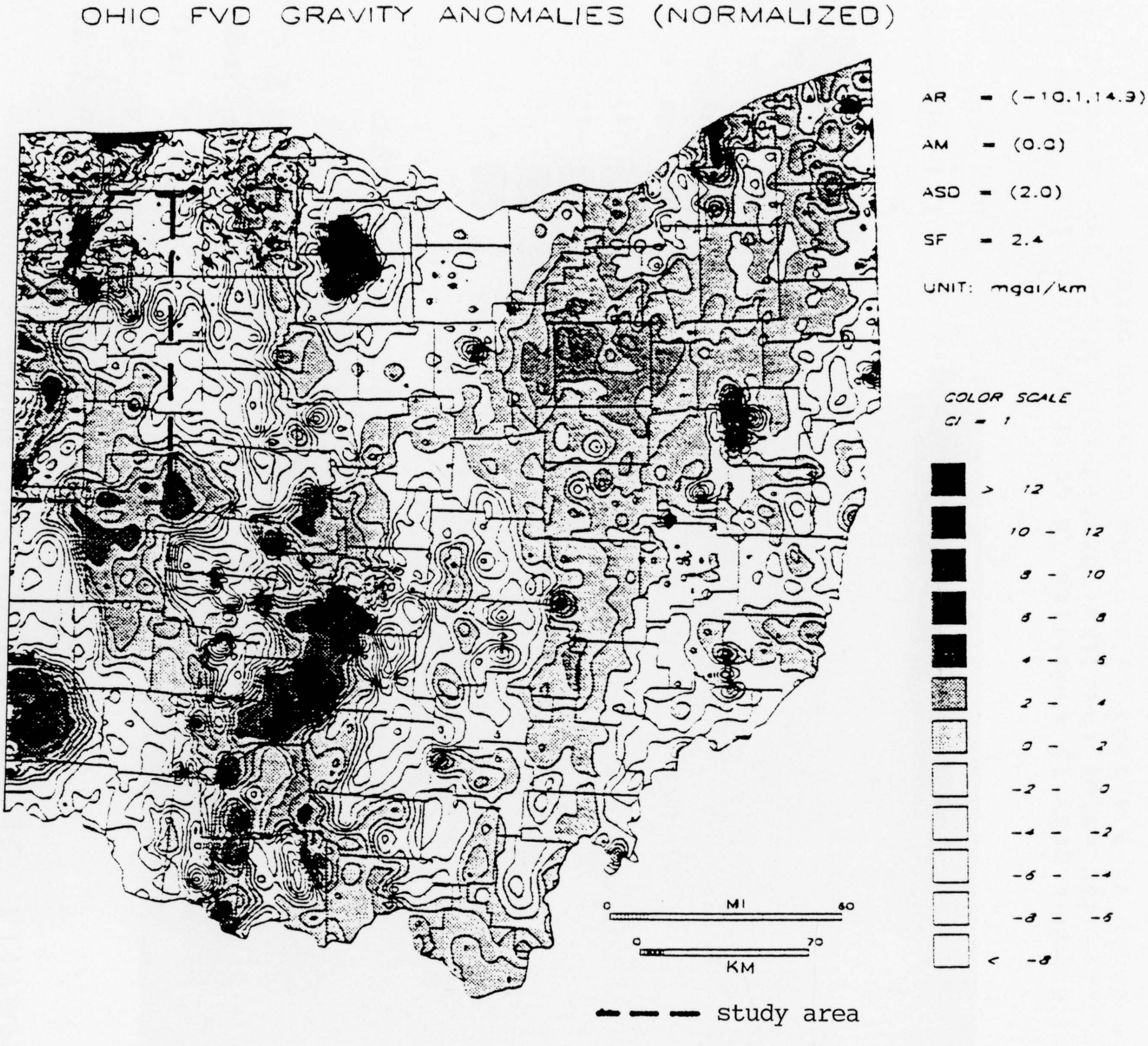

Figure 9. First vertical derivative of Bouguer gravity anomalies (normalized) of Ohio (von Frese et al., 1995).

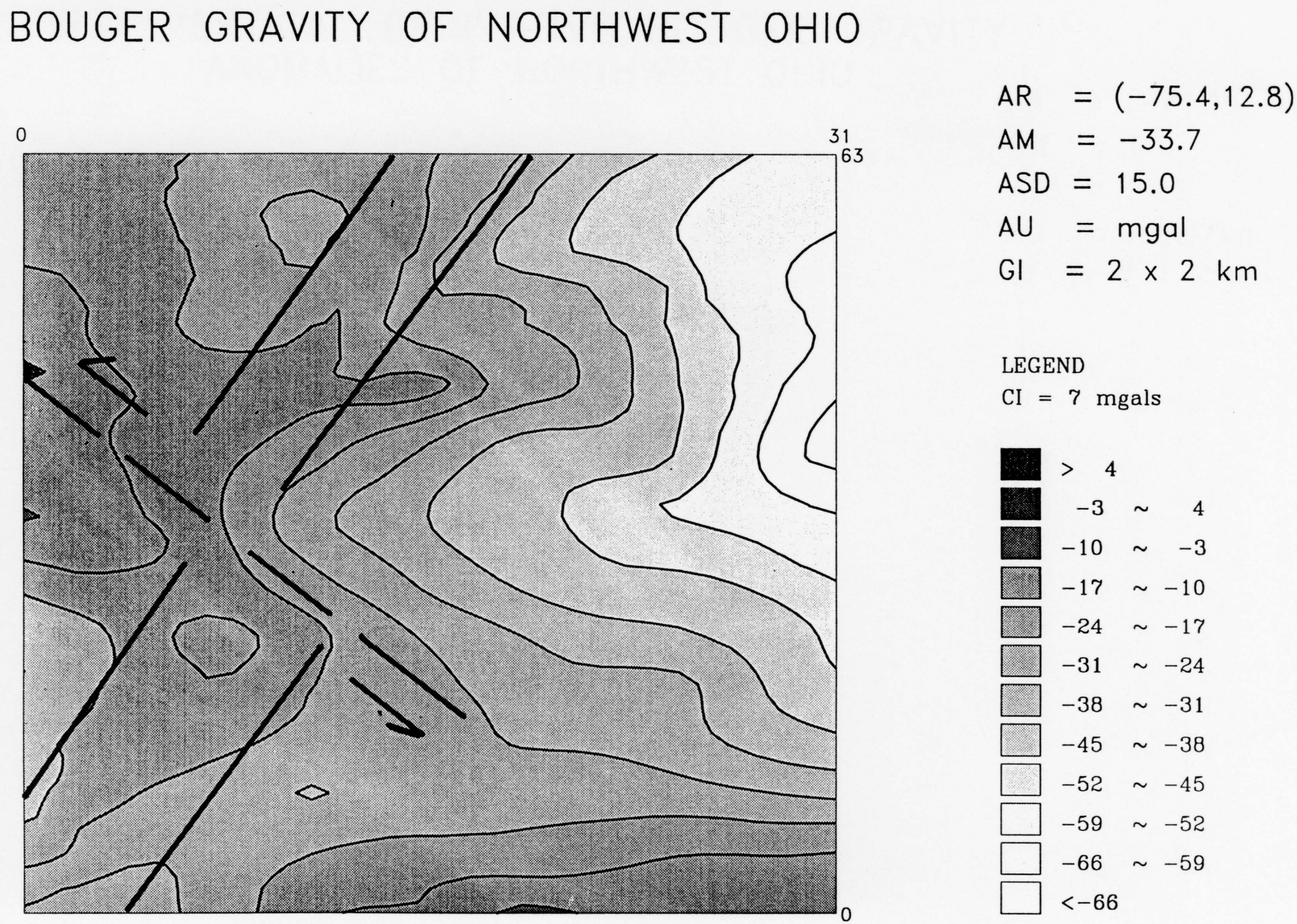

Figure 10. Complete Bouguer gravity anomalies in northwestern Ohio. Solid lines represent boundaries of the dike; dashed line shows the trace of the possible fault with arrows indicating relative offset.

FIRST VERTICAL DERIVATIVE BOUGER GRAVITY
ANOMALIES OF NORTHWEST OHIO

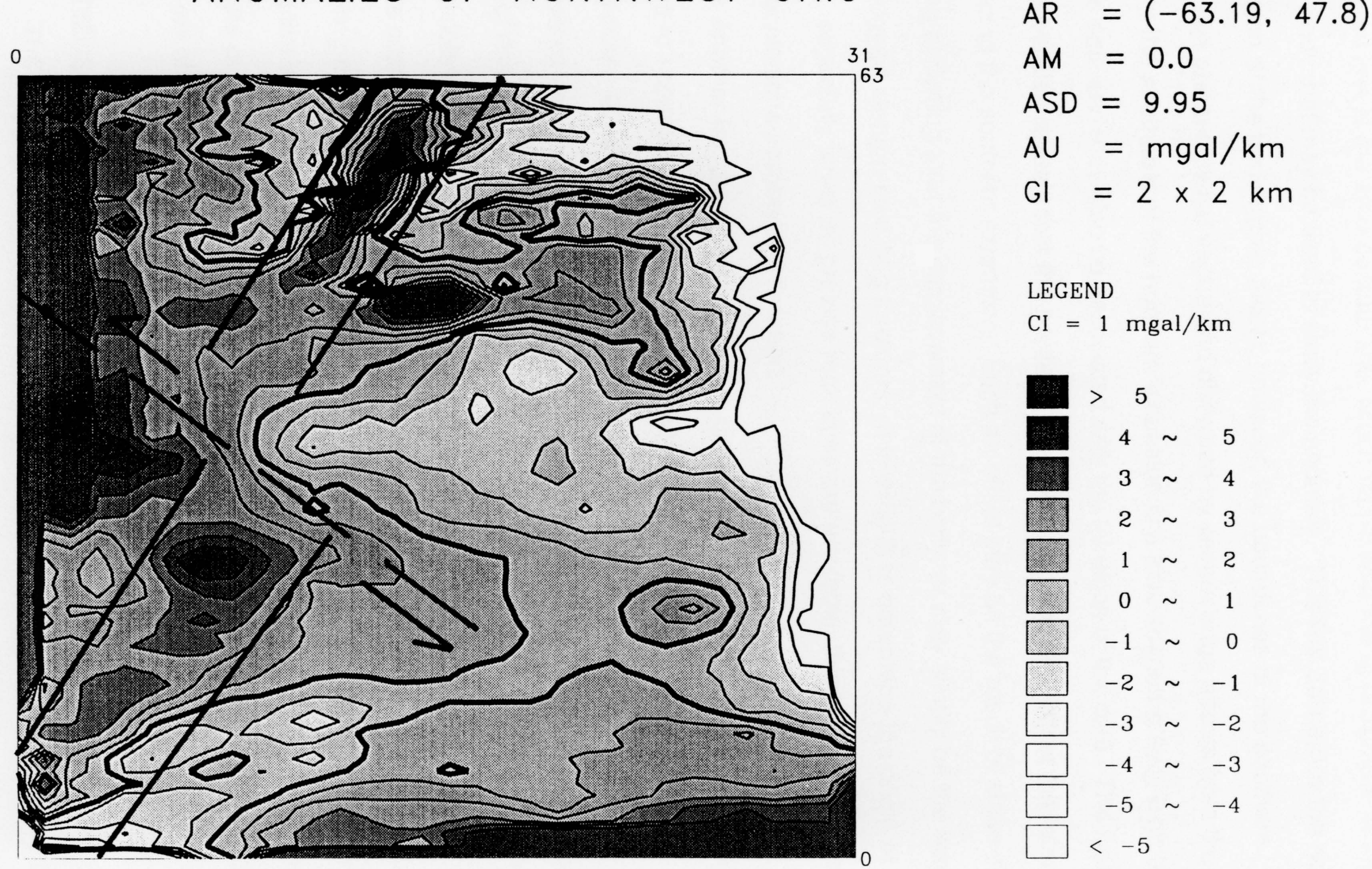

Figure 11. First vertical derivative of Bouguer gravity in northwestern Ohio. Solid lines represent boundaries of the dike; dashed line shows trace of possible fault with arrows indicating relative offset.

thickened line is the zero contour line, which represents the approximate lateral extent of the body that may be used to study the anomaly. This line delineates the northern extension of the body rather nicely; however, the boundaries of the southern extension are somewhat vague and disturbed by severe edge effects from the filtering. Just to the southeast of the northern extension is a lobe-shaped gravity high that strikes east and may also be associated with the intrusion of the dike. The first derivative also reveals that the northern extension of the dike is offset left-laterally with respect to the southern extension. Such an offset may be the result of strike-slip faulting occurring after the emplacement of the body, or may simply be the way the dike formed along preexisting fractures. It is difficult to determine the origin of the offset, especially since no precise rock ages are available; this topic is reconsidered in the conclusions section of this report.

Another feature enhanced by the derivative data is the large gravity low that seems to separate the northern and southern extensions of the dike complex. Due to this feature, it is difficult to determine whether or not the two bodies should be interpreted as being connected. It appears, however, that a gravity high exists to the west of this large low, which may represent the extension of the dike through this area. A possible explanation for the subdued anomaly signal through this area is that the dike is seated deeper in the crust here than to the north and south; two dimensional modeling may help to prove this. It should also be noted that the large gravity maxima along the western and southern borders are produced by edge effects and hence are artifacts of processing and should not be interpreted as as huge anomalies related to features of the subsurface.

Magnetics

The magnetic data used in this study were also taken from work done by Lucius (1985) (figure 12). The data were obtained from the USGS on an open-file computer

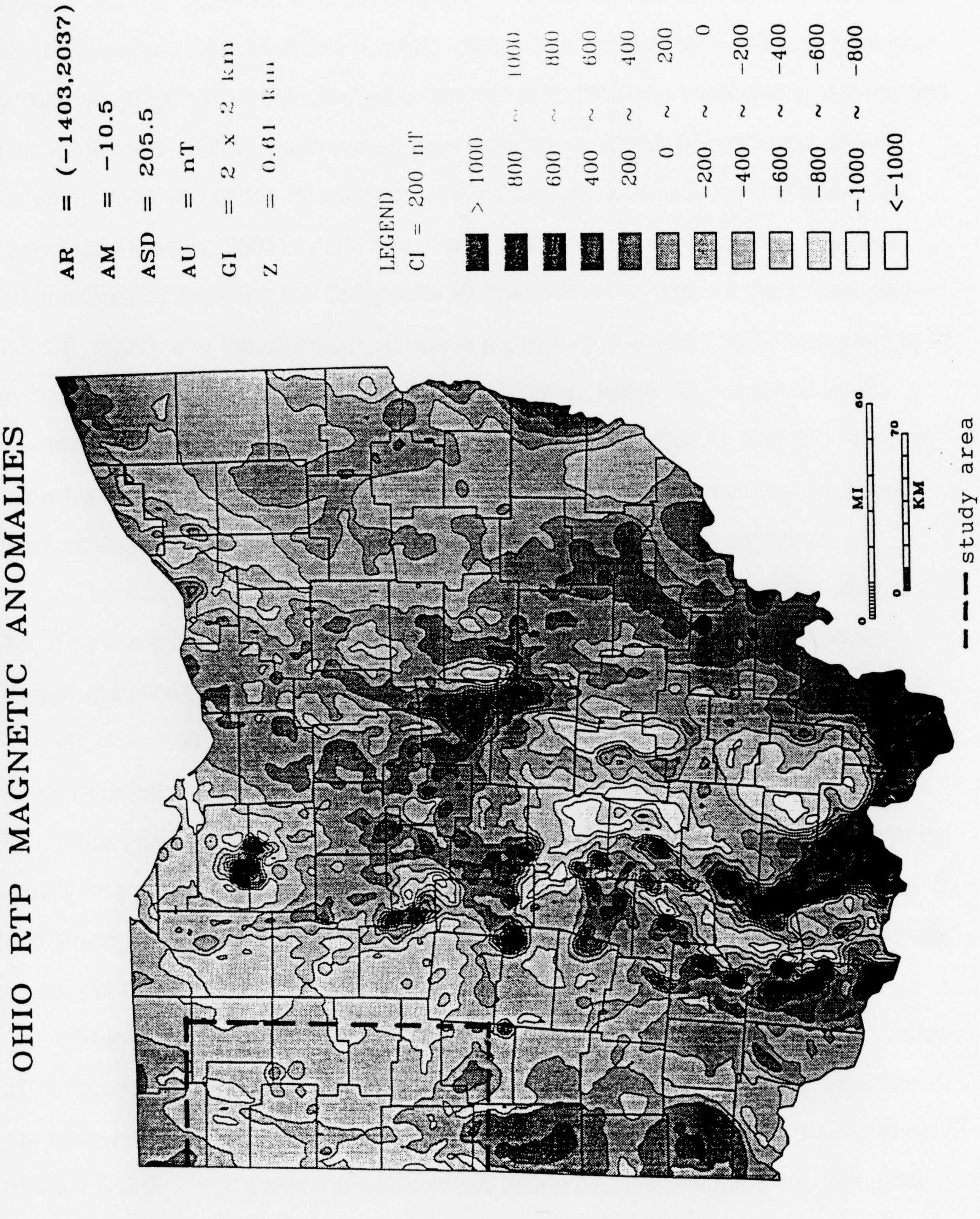

Figure 12. Reduced-to-pole magnetic anomalies of Ohio (von Frese et al., 1995).

tape, which was compiled from six different aeromagnetic surveys flown at different times, spacings, and elevations (Lucius, 1985). The residual total intensity anomaly grids were projected to the Lambert conformal projection and regridded at a 1-km grid interval (Lucius, 1985). Each survey area was then analytically continued onto a datum surface of 0.61 km (2000 ft) barometric altitude, and base level adjustments were made (Lucius, 1985). Also, a minimum rind of 40 km was attached to reduce edge effects by digitizing the Composite Magnetic Anomaly Map of the United States (USGS, 1982), and the minimum curvature procedure of Swain (1975) was used to fill in missing data over major urban complexes (Lucius, 1985). The residual total intensity magnetic data were then regridded at 2-km (256 columns and 256 rows) to allow for comparison with the gravity data (Lucius, 1985). The original data file was then reduced to 31 columns and 64 rows to concentrate on the study area.

The reduced-to-the-pole magnetic data for the study area are shown in figure 13. The linear magnetic high is easily identified and extends from the southwest corner up to the top of the figure, and strikes northeast. This anomaly represents the dike structure and corresponds spatially very well to the gravity data. A notable aspect of the magnetic data is that they more clearly reveal the location of the dike between its northern and southern extensions in comparison to the gravity data. As seen in the gravity, the magnetics also display a lobe extending off the eastern side of the dike and striking east. The magnetic data also display a more precise location of the point where the dike may be shifted left-laterally (marked by the dashed line).

The first vertical derivative of magnetics was computed using the same Fourier-2D program that was used for the gravity, and is shown in figure 14. The resolution of the anomaly is somewhat enhanced and has been surrounded by a thickened zero contour line that represents the approximate lateral boundary of the dike. It is quite easy to see the extension of the feature into Indiana to the southwest and the point at

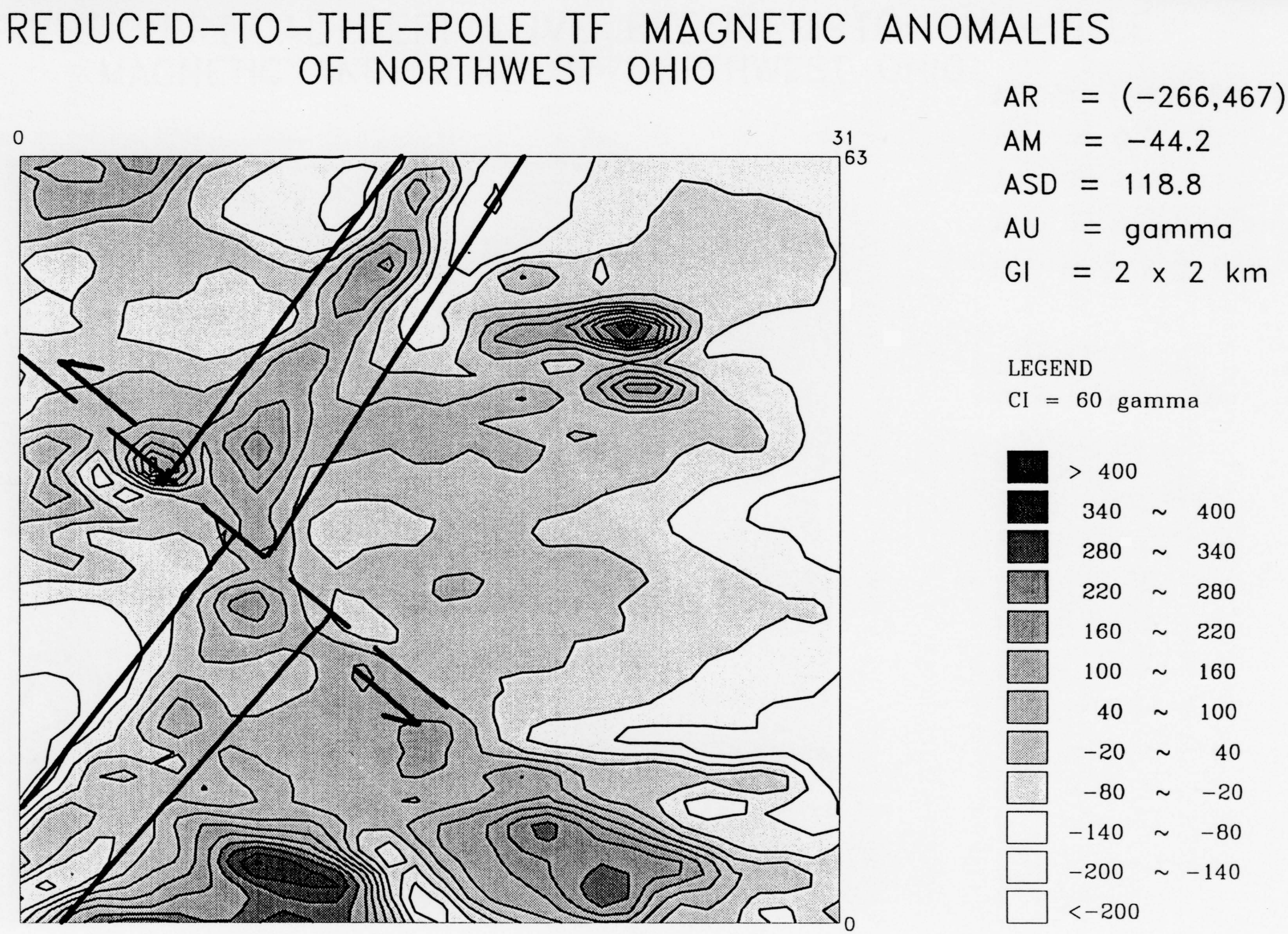

Figure 13. Reduced-to-pole magnetic anomalies of northwestern Ohio. Solid lines represent boundaries of the dike; dashed line shows trace of possible fault with arrows indicating relative offset.

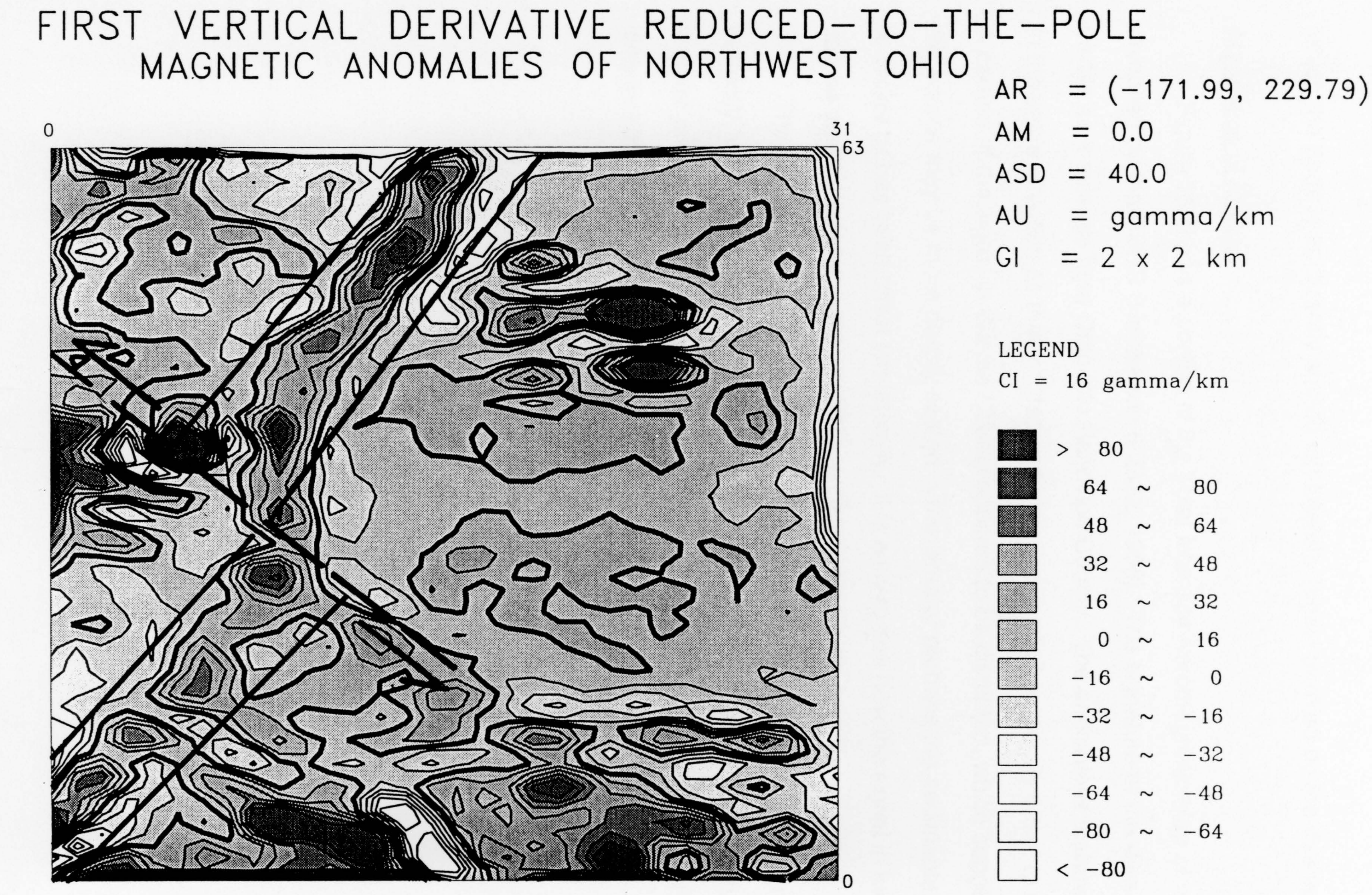

Figure 14. First vertical derivative of reduced-to-pole magnetic anomalies in northwestern Ohio. Solid lines represent boundaries of the dike; dashed line shows the trace of the possible fault with arrows indicating relative offset.

which the body is apparently shifted left-laterally (again marked by the dashed line).

Magnetics of Indiana

Figure 15 shows a portion of the Total Intensity Aeromagnetic Map of Indiana as compiled by the USGS (Henderson & Zietz, 1958). The signature of the dike is clearly visible as it extends from Ohio into Randolph County. The anomalous feature trends in the same direction as that in Ohio and also appears to be laterally offset to the left. A portion of the signal in Wayne County appears to be disrupted, which suggests that the source may be more deeply seated in this area or perhaps the sedimentary cover is thicker or has been offset left-laterally. It is easy to see how the signal in Indiana can be viewed as an extension of that in Ohio.

The gravity and magnetic expressions of the linear anomaly correlate nearly perfectly, which gives confidence in determining the position of the dike. Also, the fact that the anomaly is represented by both gravity and magnetic maxima supports the idea that the body may be composed of igneous mafic material.

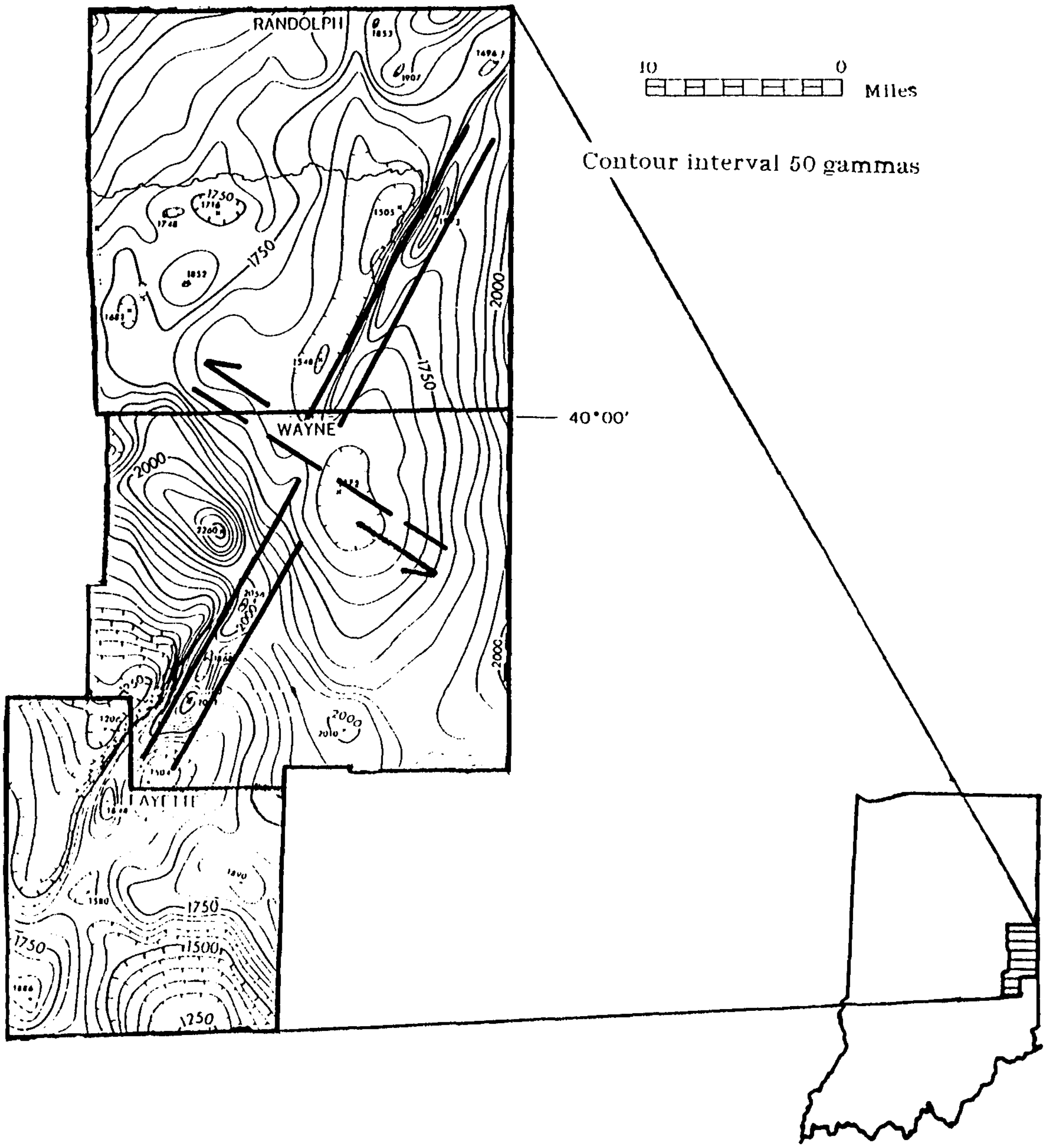

Figure 15. Total intensity magnetic anomalies of east-central Indiana. Solid lines represent boundaries of the dike; dashed line shows the trace of the possible fault with arrows indicating relative offset (modified from Leosewski, 1985).

V. TWO-DIMENSIONAL GEOPHYSICAL MODELING

Previous Models

Geophysical modeling of profiles taken across the anomaly in Randolph County, Indiana has been done by Henderson and Zietz (1958), and Leosewski (1985). Henderson and Zietz modeled the feature using magnetic methods (figure 16) and concluded that the source of the anomaly was a dike lying 3000 ft below the land surface, dipping southeasterly at a continuous 45 degrees, and extending to an indefinite depth. A susceptibility contrast of 0.008 cgs was used and is consistent with the assumption that the body is composed of mafic material.

Leosewski (1985) used gravity data as well as magnetics to model the anomaly at the same location as Henderson and Zietz (figure 17). The magnetic model proposed by Leosewski (figure 18) differs from the 1958 model in various ways. The width and depth of the source is identical to that of the Henderson and Zietz model, but Leosewski contends that the body initially dips ~75 degrees to the southeast for 4 km and then becomes essentially vertical. Leosewski also adds a cap of higher susceptibility representing a susceptibility contrast with the overlying sedimentary rocks of 0.008 cgs, while a value of 0.0065 is used for the rest of the body. This suggests a smaller contrast with the granitic country rock than the 1958 model.

The gravity modeling by Leosewski (1985) (figure 19), likewise uses a profile taken at the same location. The form of the source in this model is consistent with that used in the magnetics, with a cap of higher density contrast (0.35 mgal) reflecting the contact with the much lesser density sedimentary units.

Modeling in Ohio

For this study, gravity modeling was done using the GRAV2D computer program adapted to PV-Wave graphics by Hayden (1993) at the Ohio State University.

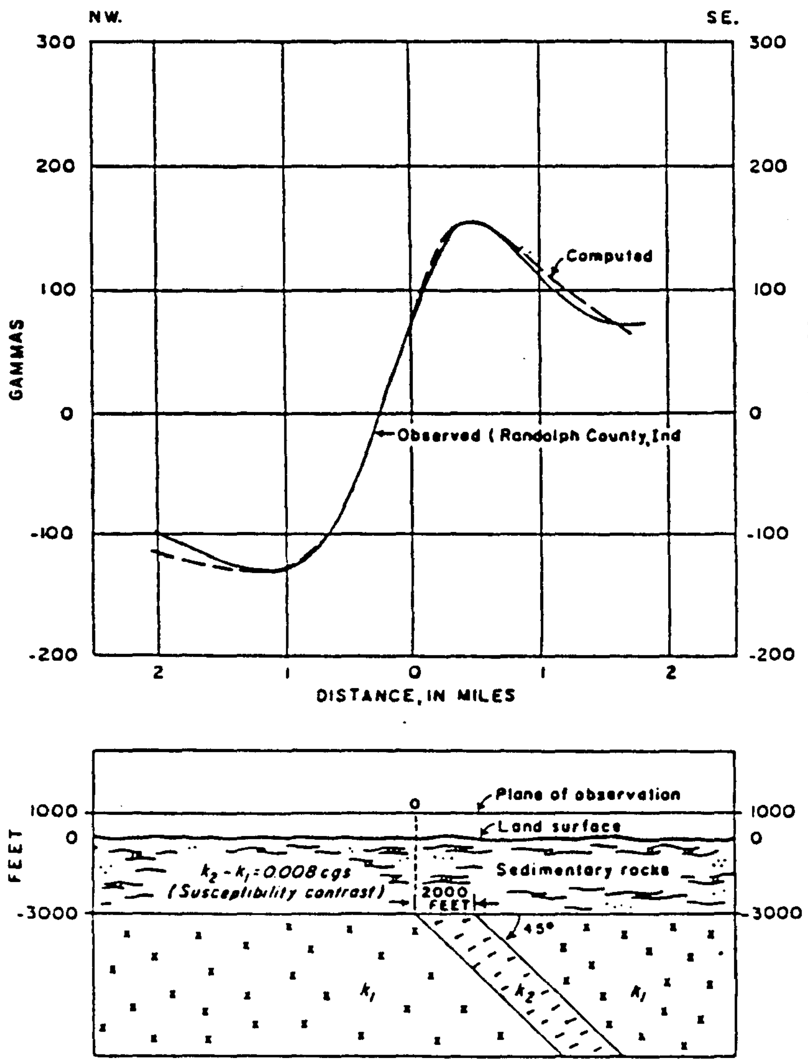

Figure 16. Dike model proposed by Henderson and Zietz in 1958 study of east-central Indiana anomaly.

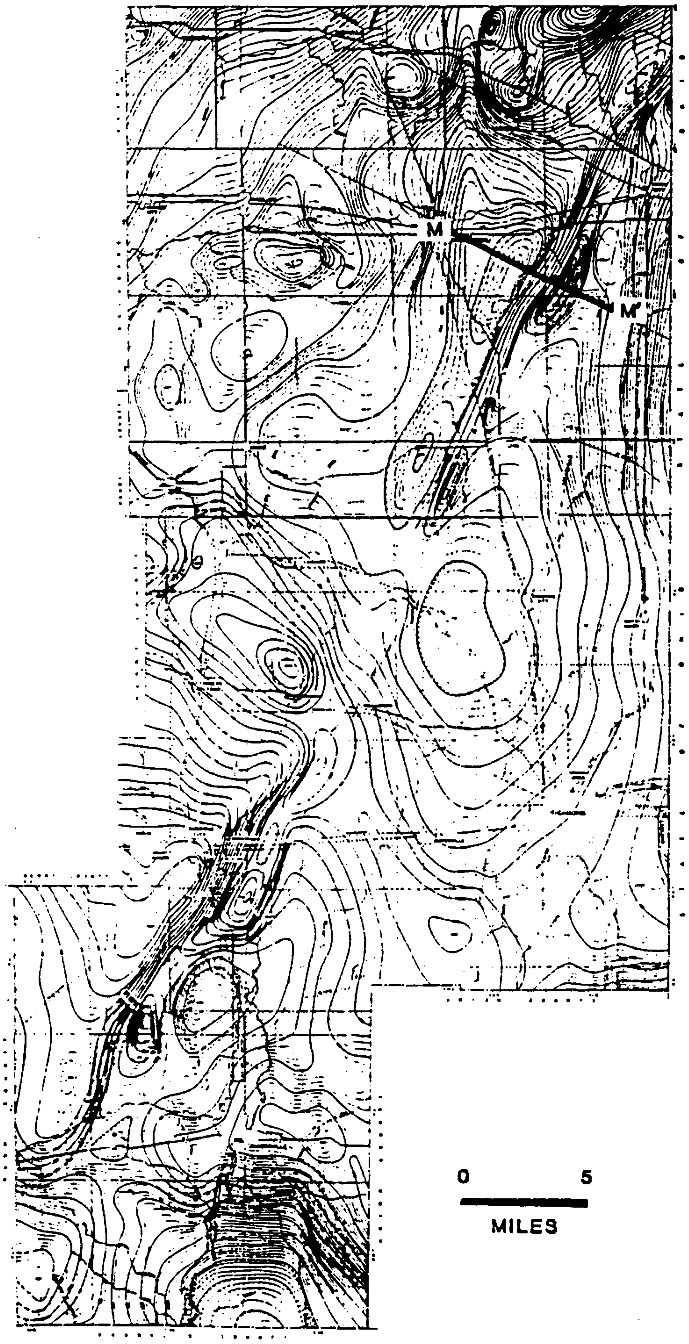

Figure 17. Total intensity aeromagnetic map of Randolph, Wayne, and Fayette Counties, Indiana showing location of profiles modeled by Leosewski and Henderson and Zietz(1958) (Leosewski, 1985).

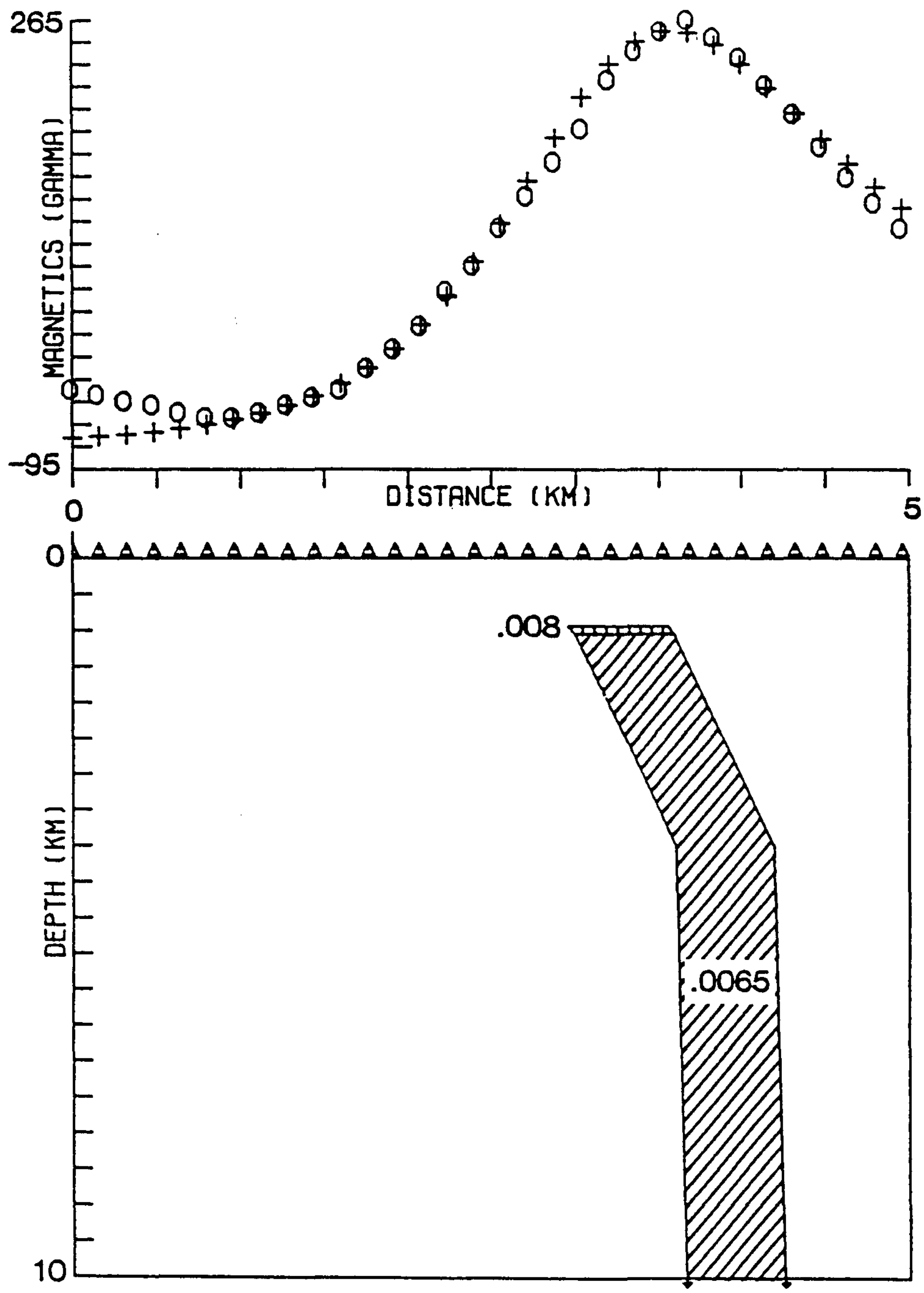

Figure 18. Magnetic model M-M´ (O is observed anomaly, + is calculated anomaly) (Leosewski, 1985).

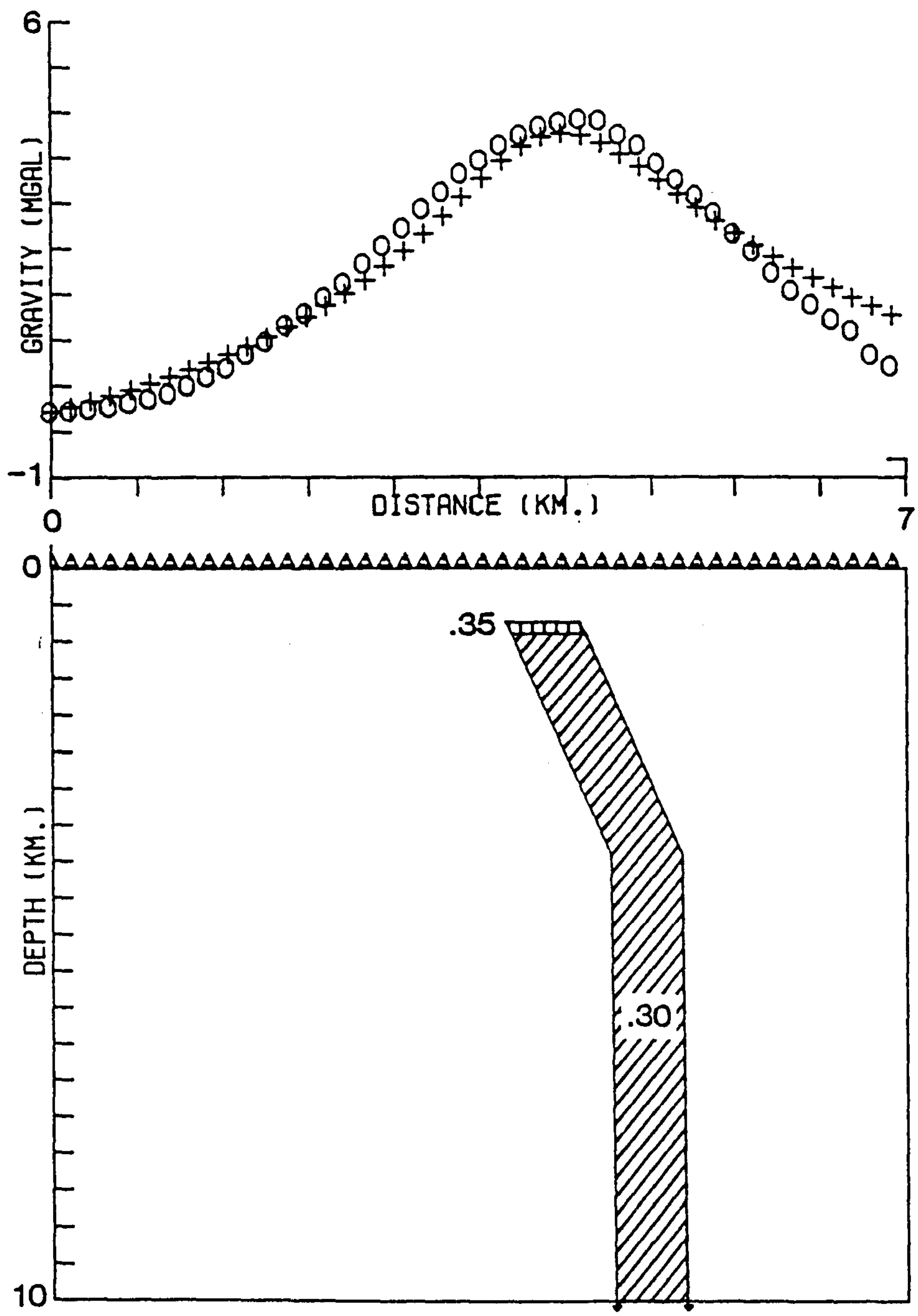

Figure 19. Gravity model G-G′ (O is observed anomaly, + is calculated anomaly)(Leosewski, 1985).

Two profiles were taken approximately perpendicular to the trace of the anomaly (figure 20). Comparison of both the A-A' and the B-B' models with those already discussed, reveals similarities and differences.

The observed values for profile A-A' (figure 21) were taken directly from the gravity data described earlier, then the regional signal was removed (figure 22) and the line extended ~8.5 km into Indiana using data from a gravitational intensity map compiled by the Indiana Geological Survey (1953). The regional gravity expressed in the area containing profile A-A' is represented by low magnitude gravity signals and is interrupted by the higher gravity expressions of the linear anomaly under study and another source to the southeast (figure 20). The most notable difference between the A-A' model and that of Leosewski is the increase in intensity of the anomaly signal from ~5 mgal, to over 11 mgal in the A-A' profile. The lateral extent of the signal is also greater, spanning 50 km as compared to what appears to be just over 7 km in the Leosewski model. These two factors have resulted in a much wider (2.5 km-3.0 km) source, which is shown in the model as body 3. This suggests that the feature is probably a swarm of parallel dikes instead of one giant intrusion. One possible explanation of these differences may be that in Ohio, the top of the feature has been planed off by uplift and erosion leaving only the thicker, more massive base as the cause of the anomaly. While in Indiana, such planing has not occurred and the less massive top of the feature can be modeled. Also, the larger lateral extent of the signal has resulted in a much deeper seated position (~3.5 km) below the land surface. The source is shown dipping to the southeast at a constant angle of 37 degrees, which although less steep, is more closely related to the model of Henderson and Zietz than to Leosewski. As in Leosewski, a density contrast of 0.300 mgal was used, but without the higher density cap. The model also shows various smaller bodies that have been added in order to match the observed signal at the flanks of the profile. The

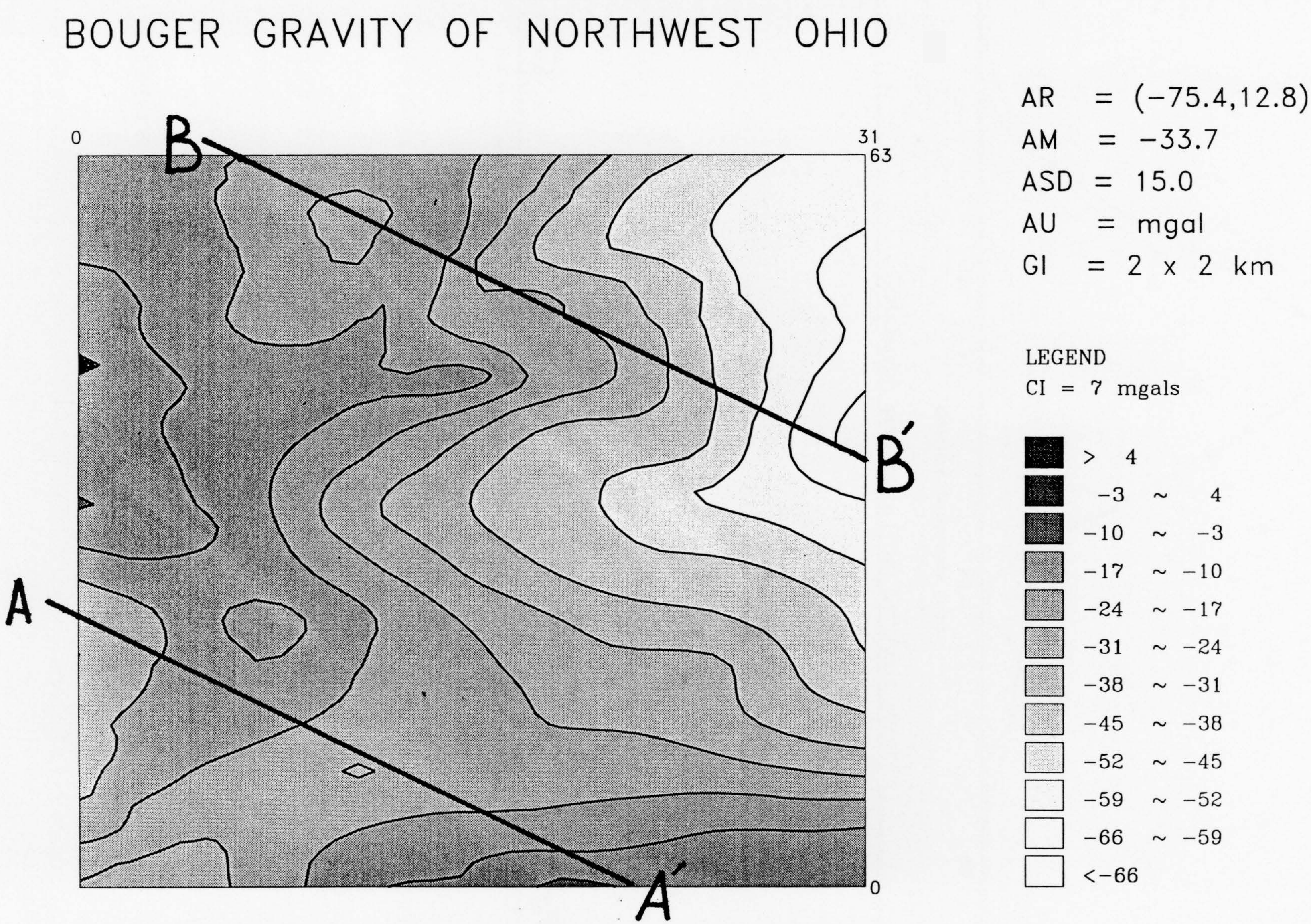

Figure 20. Location of gravity profiles A-A' and B-B'.

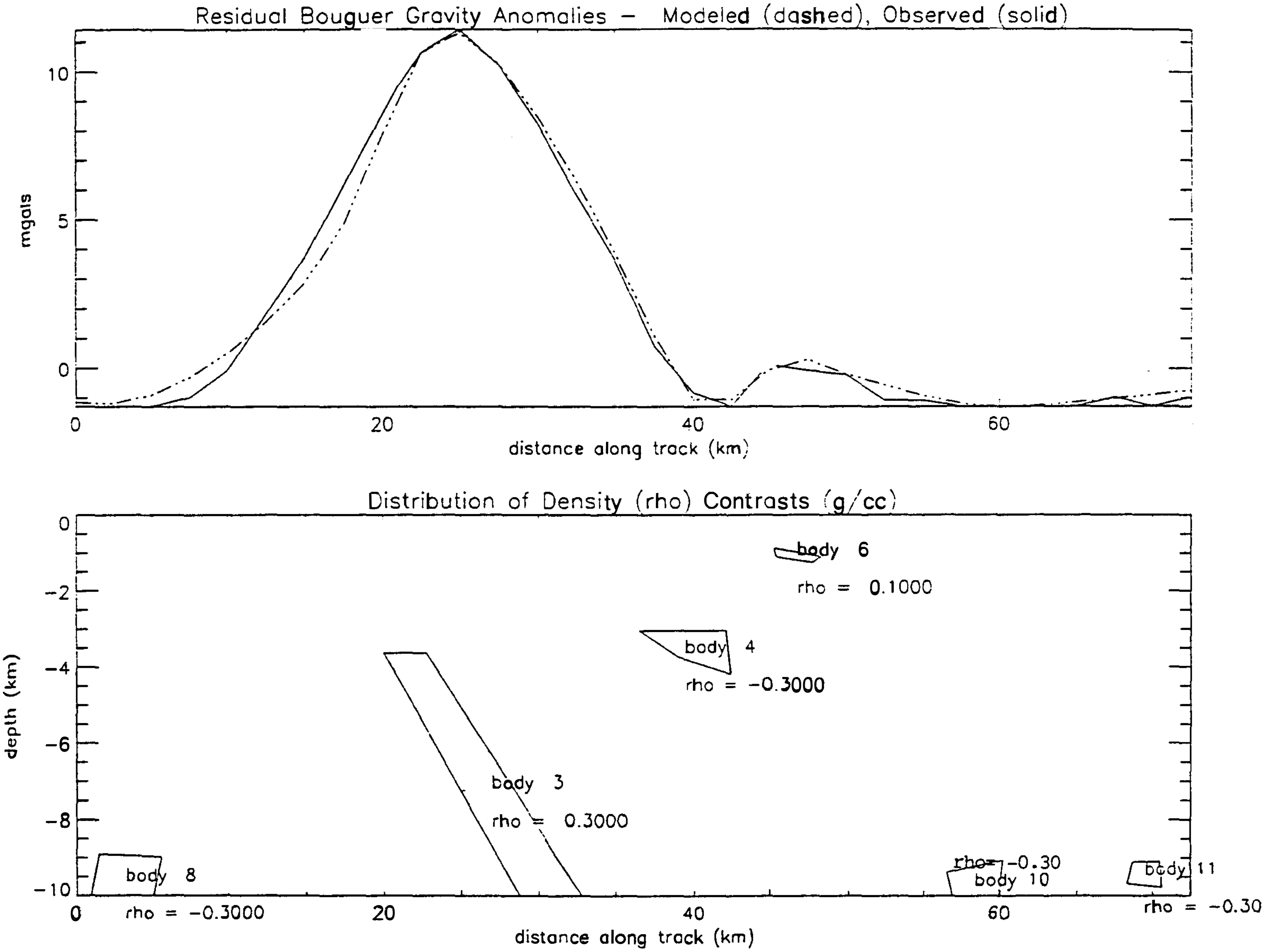

Figure 21. Gravity modeling of profile A-A'.

A-A′

B-B′

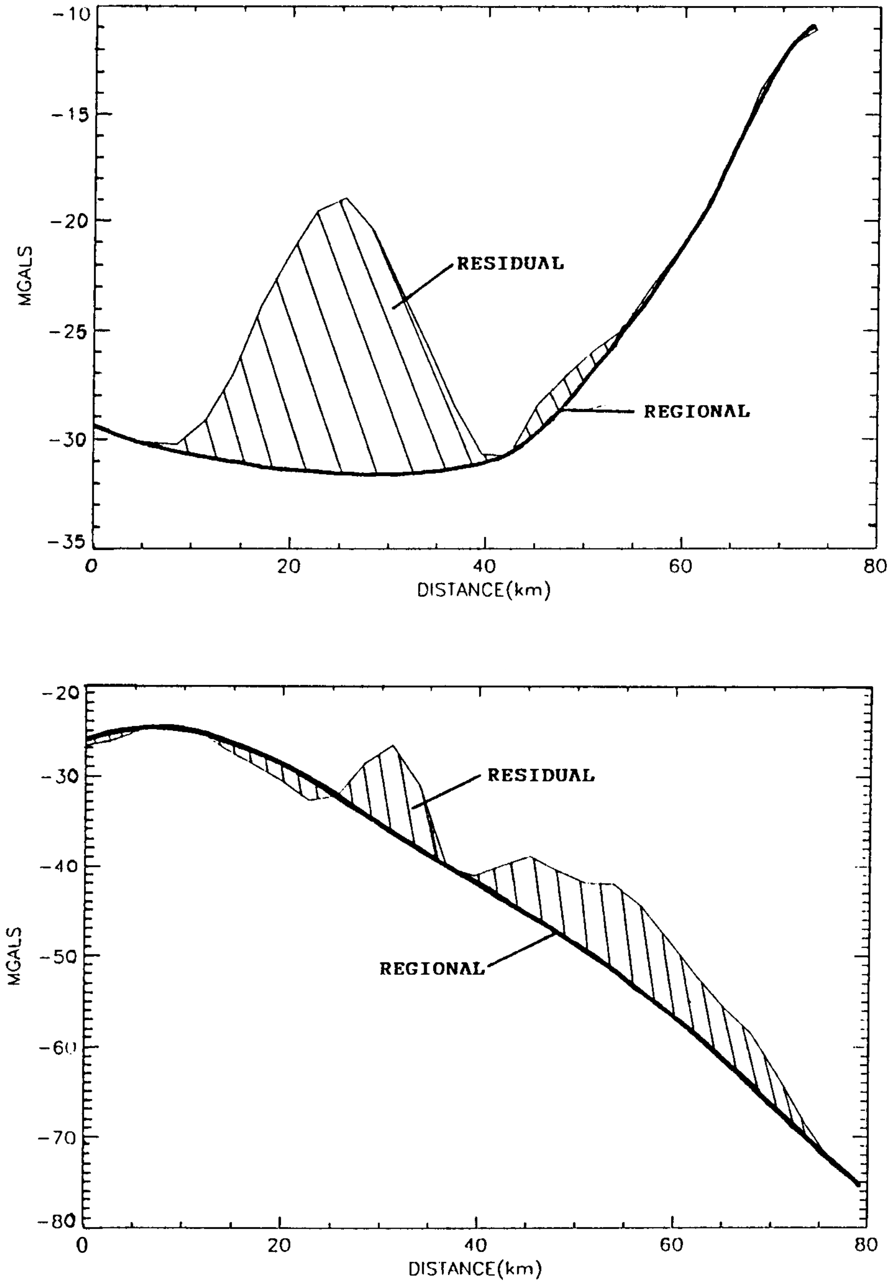

Figure 22. Gravity profiles used for 2-D modeling.

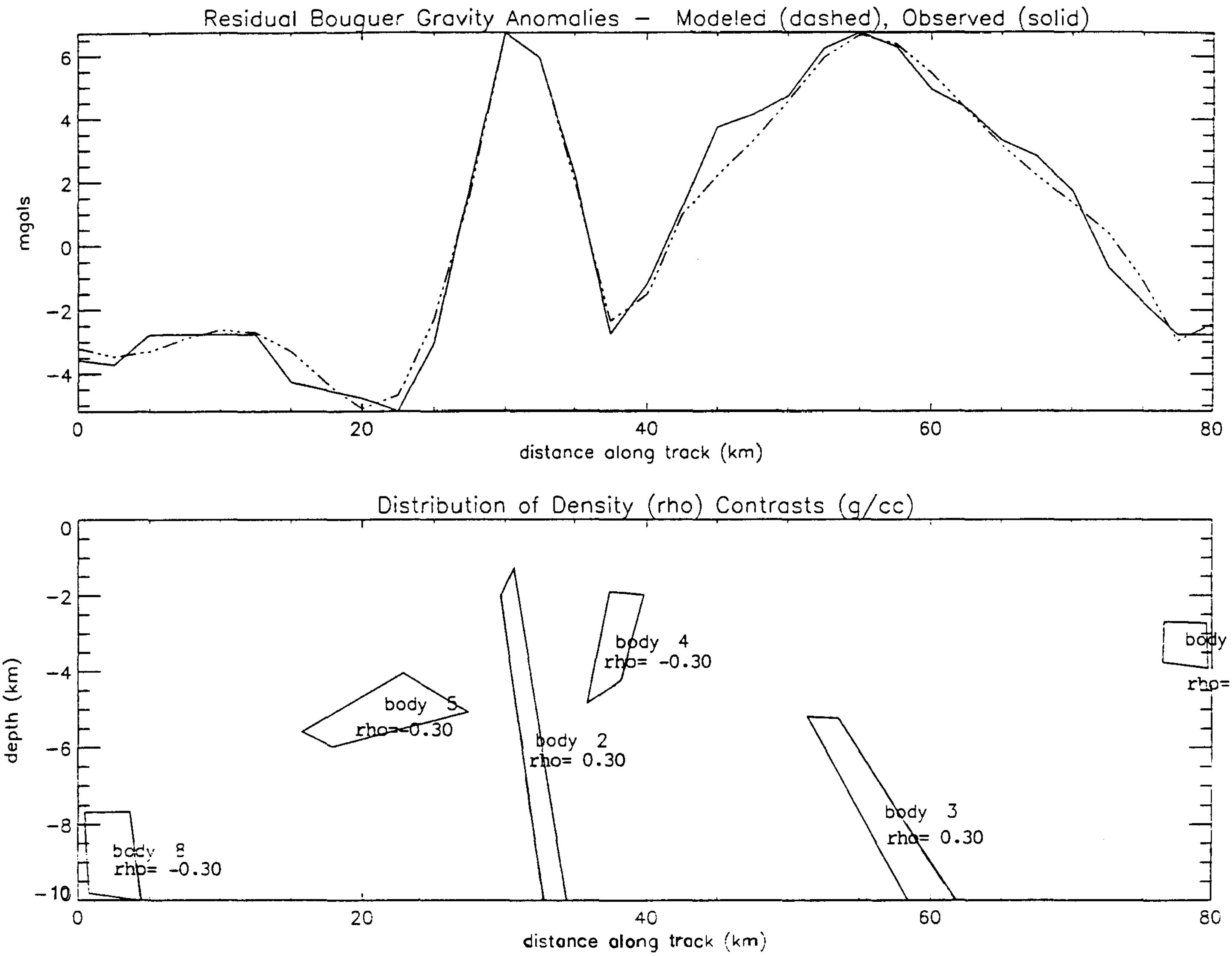

Figure 23. Gravity modeling of profile B-B'.

orientations and density values of these bodies have not been formally studied and they therefore represent only a possible solution to the observed signals produced in the subsurface along the flanks.

Profile B-B' (figure 23) was also produced from the previously described gravity data, that have also had the regional signal removed (figure 22). The regional gravity expression of the area containing profile B-B' is represented by a general increase in the magnitude of the gravity signal from east to west, which is interrupted by the linear gravity high produced by the anomaly under study and a gravity low immediately to its west. The source, shown in this model as body 2, more closely resembles the feature as modeled in Indiana. It is both narrower (~1.25 km) and less deep (~1.25 km) than the source shown in A-A'. Although the source is narrower, it is still approximately twice the width of that proposed by Leosewski, still suggesting a dike swarm. The source in this model also dips to the southeast, but at a much steeper angle of ~71 degrees. Like the A-A' model, a density contrast of of 0.30 mgal was used with no higher density cap. Several other bodies were also added to this model to make a general match with the observed signal generated at the flanks of the anomaly. Body 3 is of particular interest as it may represent another dike-like intrusion oriented similarly to body 2. Perhaps this body is an extension of the main dike complex or a related separate intrusion.

Results of Modeling

Modeling of the linear anomaly in both Indiana and Ohio suggest that the source is a mafic dike complex having a density contrast with the granitic country rock of 0.30 mgal and dipping to the southeast at between 37 - 71 degrees.The feature appears to be narrower and more shallow in Indiana and becomes wider and deeper moving into Mercer County, Ohio; the body may possible become so deep as to cause an absence of the gravity signal in northern Mercer and Southern Van Wert County.

The source becomes less thick and more shallow moving into Paulding, Defiance, and Williams counties, and may continue in this manner into Southern Michigan.

The differences that are seen between earlier models and those of this study may be in part related to the fact that the previous models used only the crest of the anomaly. A span of only 5 km was used in Henderson and Zietz (1958), and one of only 7 km was used in Leosewski (1985). This exclusion of the flanks of the anomaly must surely be a source of discrepancy when comparing these models to those of this study which cover nearly 80 km. The larger profile provides a more complete model as it takes into account the entire gravity signal, including that of the anomaly under study and the surrounding area.

VI. CONCLUSIONS

Geophysical investigations have determined the source of a large, linear gravity and magnetic anomaly extending from east-central Indiana and through northwestern Ohio may be an intrusive mafic dike or dike complex. The feature is likely to be Keweenawan in age and is probably the result of rifting along preexisting zones of weakness (Leosewski, 1985).

Geophysical modeling has determined the possible source to be between 1000 meters and 3500 meters below the surface and dipping to the southeast at between 35 degrees and 71 degrees. The source is probably composed of mafic material having a density of approximately 2.8 g/cc, producing a density contrast with the surrounding country rock of 0.30 g/cc. Also, the source may be modeled by an effective magnetic susceptibility of 2596×10^{6} cgs, producing a susceptibility contrast with the country rock of 0.0065 cgs units (3.53 A/m), and a susceptibility contrast with the overlying sedimentary rock of 0.008 cgs units (4.71 A/m) (Leosewski, 1985). The absolute age of the intrusion is not known but it is thought that the feature is emplaced only in the Precambrian country rock and not in the overlying Paleozoic sedimentary rocks (Henderson & Zietz, 1958); thus the body must be older than Paleozoic in age.

The intrusion appears to be offset in a left-lateral manner in at least two areas along its length. This may be the result of strike-slip movement along northwesterly trending faults, which have been described in Ohio by Jones (1988), as shown in figure 24. The trace of the strike-slip fault in this figure runs precisely through the point of offset proposed earlier in this study. Left-lateral strike-slip movement has also been described in southern Michigan (figure 25) by Ells (1962), Buehner & Davis (1968), and Harding (1974). The faults are described in this region as trending N30W and producing offsets between 1.5 km to 4.0 km. The faults are thought to have

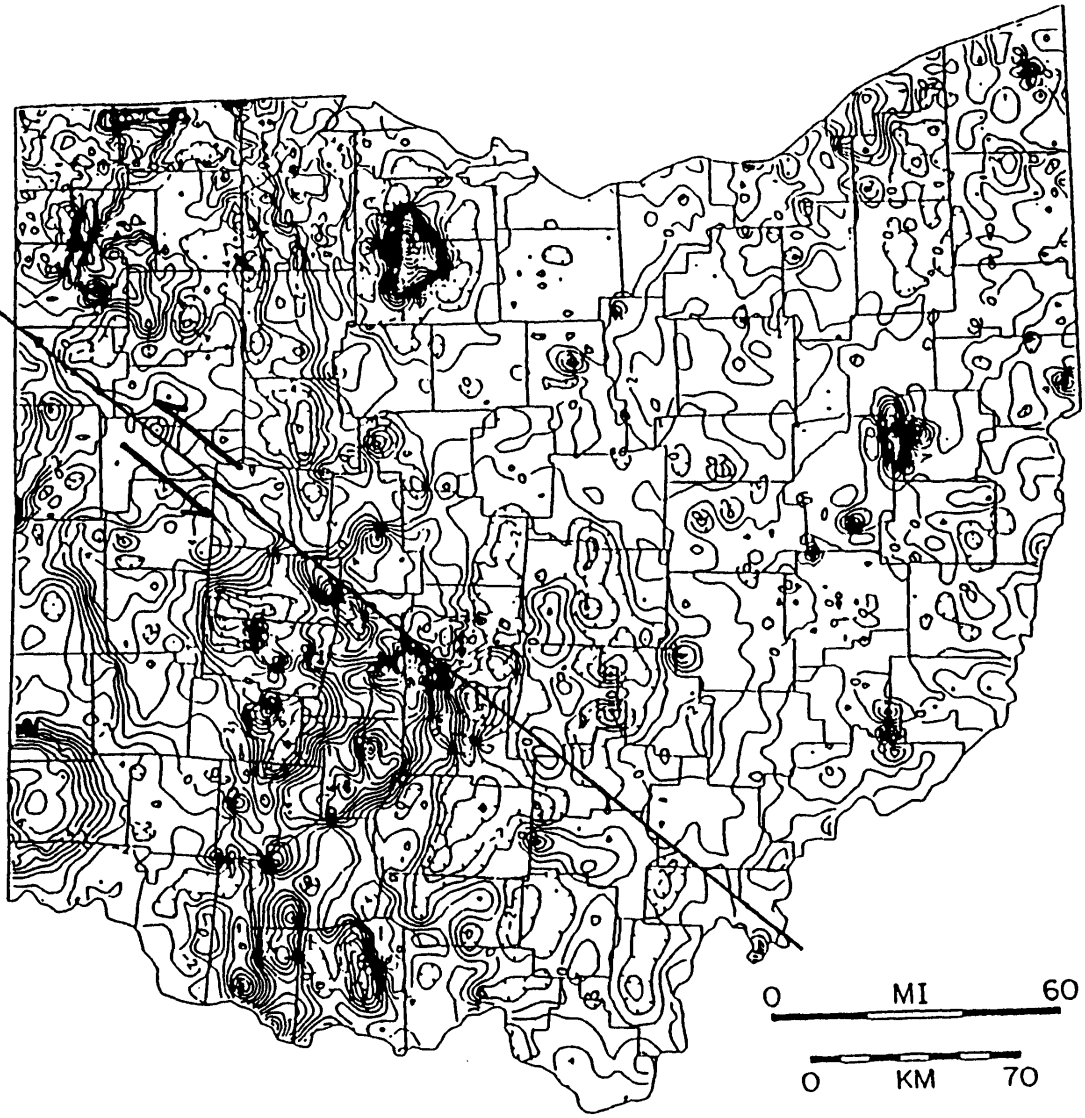

Figure 24. Location of possible strike-slip movement in Ohio with arrows showing relative offset (modified from Jones, 1988).

Figure 25. Traces of major anticlines and faults (thick lines) within the Michigan Basin (modified from Petroleum Information, 1984).

formed during the Precambrian and then reactivated during the Paleozoic, possibly as a result of compression brought on by the Acadian Orogeny in the Early Devonian (Dott & Batten, 1981).

The northern extension of the dike may reach into southern Michigan and be associated with the formation of the Albion-Scipio and Stoney Point oil fields (figure 26). These fields traverse Calhoun, Jackson, and Hillsdale counties covering over 58 sq. km (Hurley & Budros, 1990). The hydrocarbons of these fields have accumulated in synclinal sags of the Trenton Limestone/Black River formations (Ordivician) due to dolomitization and karstification of these units related to basement faulting (Hurley & Budros, 1990) like that described above. Leosewski (1988) describes a similar cause of hydrocarbon accumulation in the Trenton Limestone of Indiana. However, Leosewski reports that dolomitization and karstification here are due to zones of weakness produced in the sedimentary beds that were draped over the top of the basement ridge associated with the intrusion of the dike complex. He also suggests that similar processes may be responsible for oil and gas reservoirs in the Trenton of Ohio, such as the Indiana-Lima field. An interesting point to note is that the Stoney Point field in Michigan was discovered only recently (1982), and hence other fields may still be hidden in the Trenton units along the dike swarm in the tri-state region.

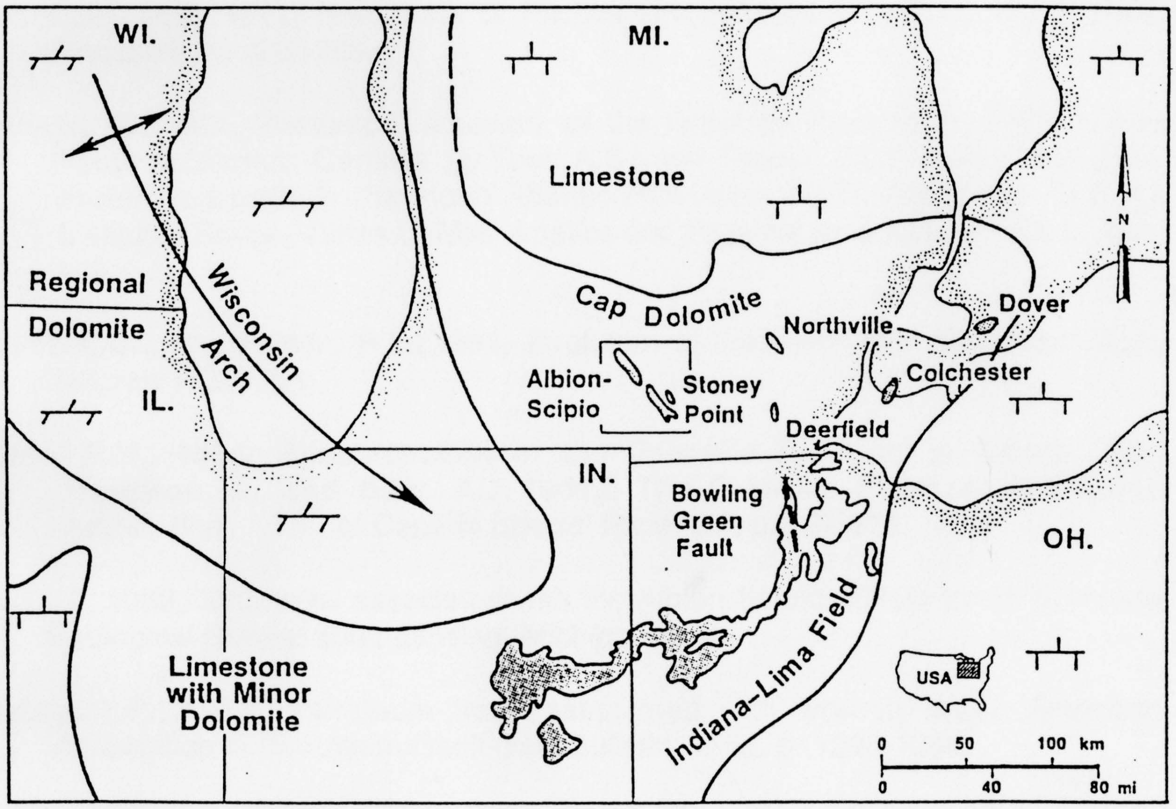

Figure 26. Map showing oil fields of the Trenton Limestone in the Great Lakes region of the United States (K.K. Landes, 1970).

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